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MULTI-DECADAL VARIABILITY IN THE BERING SEA: A SYNTHESIS OF MODEL RESULTS AND OBSERVATIONS FROM 1948 TO THE PRESENT

by

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December 2013

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13. ABSTRACT (maximum 200 words)

The northern Pacific Ocean is a highly dynamic region characterized by strong decadal signals, as evident in climate regime shifts. A regime shift marks when the climate exhibits an abrupt modification from one physical environment to another. The mesoscale variability seen in regime shifts is poorly represented in earth system models. To best understand the changes in the Arctic Ocean, we must analyze the Pacific Ocean's influence on the Arctic through regional models.

This study synthesizes multi-decadal results in the Pacific Ocean from the regional Arctic system model (RASM); a high-resolution, pan-Arctic, coupled model forced with atmospheric data from the Common Ocean Reference Experiment, version 2 (CORE2), 1948–2009 reanalysis to identify climate regime shifts. Analyzed results are validated with observational data and compared to output from the, community climate system model, version 4 (CCSM4). RASM demonstrated skill in identifying climate regime shifts. RASM-based correlations with the Pacific decadal oscillation (PDO) can explain 40–60 percent of the total variability in the northern North Pacific and Bering Sea region. Limited comparisons of RASM to CCSM4 suggest there is added value in regional climate simulations and better understanding of climate regime shifts.

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	Alaskan Index
ALPI	Aleutian Low Pressure Index
AO	Arctic oscillation
AOR	areas of responsibility
C4ISR	computers, intelligence, surveillance, and reconnaissance
CCSM4	community climate system model version 4
CESM	community earth system model
CICE	community ice model
CISM	community ice sheet model
CMIP5	Coupled Model Inter-comparison Project Phase 5
CNO	Chief of Naval Operations
CORE	Common Ocean–Ice Reference Experiments
CRS	Congressional Research Service
DoD	Department of Defense
DoE	Department of Energy
ECMWF	European Center for Medium Range Weather Forecasting
EKE	eddy kinetic energy
EPI	East Pacific Index
ESM	earth system models
FY	fiscal year
GC/ESM	global climate and earth system models
ICESat	Ice, Cloud, and Land Elevation Satellite
IPCC	Intergovernmental Panel on Climate Change
JPL	Jet Propulsion Laboratory
LANL	Los Alamos National Laboratory
MDA	maritime domain awareness
METOC	meteorology and oceanography
MIZ	marginal ice zone
NAME	Naval Postgraduate School arctic modeling effort
NASA	National Aeronautics and Space Administration

NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NPICPC	North Pacific Index from Climate Prediction Center
NPINCAR	North Pacific Index from National Center for Atmospheric Research
NSF	National Science Foundation
NSS	National Security Strategy
OGCM	ocean general circulation models
OSD	Office of the Secretary of Defense
PDO	Pacific decadal oscillation
PNA	Pacific North American Index
POP	Parallel Ocean Program
QDR	Quadrennial Defense Review
RACM	regional Arctic climate model
RASM	regional Arctic system model
RSM	regional climate system models
SST	sea surface temperatures
STARS	sequential T-test analysis of regime shifts
UCAR	University Corporation for Atmospheric Research
UCP	Unified Command Plan
UNCLOS	United Nations Convention on the Law of the Seas
USCG	United States Coast Guard
USN	United States Navy
VIC	variable infiltration capacity

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I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

The large scale climate determines the environment for microscale (order 1km) and mesoscale (order 10km) variability, which then feeds back onto the large scale climate (Kirtman et al. 2009). Ocean general circulation models (OGCMs) in order to complete long model runs have historically provided global simulations of the oceanic circulation at resolutions that are lower than what might be otherwise considered necessary. With such configured OGCMs, there are numerous Arctic climatic processes that are omitted or poorly represented. These processes include: oceanic mesoscale eddies, tides, fronts, buoyancy-driven coastal and boundary currents, cold halocline, dense water plumes and convection, double diffusion, surface/bottom mixed layer, sea ice thickness distribution, concentration, deformation, drift and export, fast ice, snow cover, melt ponds and surface albedo, atmospheric loading, clouds and fronts, ice sheets/caps, permafrost, river runoff, and air-sea ice-land interactions and coupling (Maslowski et al. 2012).

In order to account for these mesoscale processes, the advancement of regional climate system models (RSMs) have come into development. One of the goals of RSMs is to serve as tools that will enable researchers to break down complex interactions and explore regional coupling pathways in ways that are not possible in current global earth system models (ESMs) (Maslowski et al. 2012).

Work with RSMs in the North Pacific, and specifically the Bering Sea, demonstrates the importance of high-resolution regional climate system models. For example, when investigating the flow through the Bering Strait, several challenges are presented. The strait is only 85km wide and 30 to 50m deep (Clement Kinney et al. 2012). The flow across the strait is strong and variable with horizontal velocities up to 80 cm/s (Clement Kinney et al. 2012). The width and depth of the strait and adjacent shelves with a large ocean to the north and south presents a great challenge to numerical modeling that requires a combination of high resolution and large domain to realistically

represent the time-dependent and highly variable flow (Clement et al. 2005). Results from the previous research indicated that the Naval Postgraduate School Arctic Modeling Effort (NAME) was able to represent anomalous events, such as major flow reversals, which were corroborated by observations and may have a more realistic representation of the flow through the strait (Clement et al. 2005, 2012).

Another area where regional RSMs have improved the understanding of the physical processes is the communication of the northern Pacific Ocean and the southern Bering Sea. A study by Maslowski et al. (2008) found that mesoscale eddies are found to periodically move along the path of the Alaskan Stream and alter the mean position of the typically westward flowing current. The is important as the Alaskan Stream has significant influence on the Bering Sea, as the primary source of warm and relatively fresh water that passes through the Aleutian Islands (Maslowski et al. 2008). Another study of a 26-year period from 1979–2004 found that meanders and eddies are continuously present in the Kamchatka Current, as well as elsewhere throughout the Bering Sea, and that these eddies are important in redistributing temperature and salinity that may have an effect on biological species in the region by changing environmental conditions (Clement Kinney & Maslowski 2012). The 9km horizontal resolution of the NAME model made it possible to resolve eddies with diameters as small as 36km (Clement Kinney & Maslowski 2012). Therefore, a high-resolution model is necessary to simulate these features, since they might not show up in a lower resolution global model. By doubling horizontal resolution modeled eddy kinetic energy (EKE) is increased by an order of magnitude or more (Maslowski et al. 2008). This is important in regions such as the central Arctic where eddies are commonly simulated though their typical size is 80 to 150km compared to 10 to 20km range of observed eddies (Maslowski et al. 2008).

An area that so far has not received much focus in studies using RSMs is climate regime shifts. A regime shift is defined by a characteristic behavior of a natural phenomenon that experiences an abrupt change from one characteristic behavior to another (Hare and Mantua 2000). Generally, there are climatic parameters that follow a natural characteristic or behavior over a broad spectrum of spatial and temporal scales. Attempts have been made to study regime shifts through statistical analysis. Rodionov

and Overland (2005) developed a method based on sequential t-test analysis of regime shifts (STARS) to take 45 indices to try and identify historical regime shifts (see Figure 1). The study was able to identify regime shifts in 1943, 1977, 1989, and 1998 (Rodionov and Overland 2005).

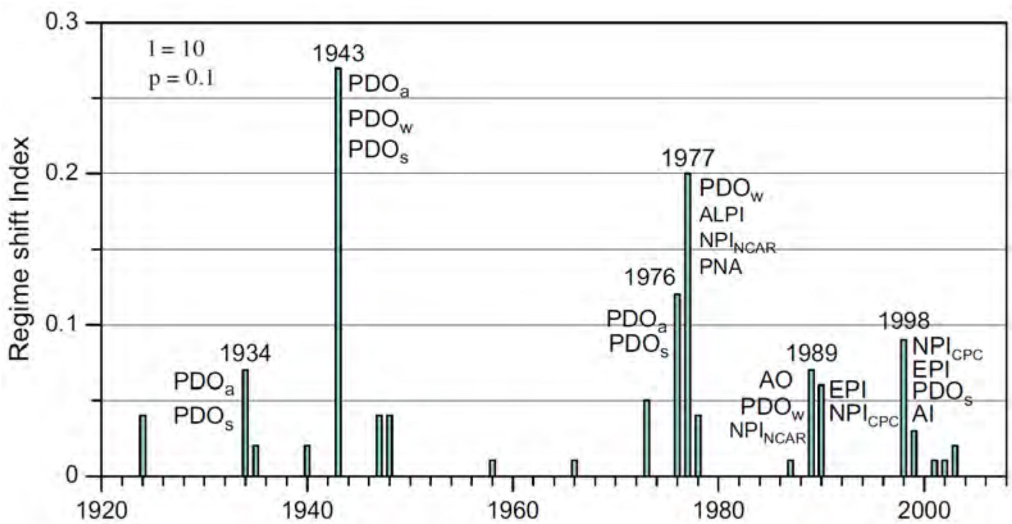

Figure 1. Regime shift index values for the group of climate indices (Pacific decadal oscillation [PDO]; subscripts a, w, and s, annual, winter, and summer values, respectively); Aleutian Low Pressure Index [ALPI]; North Pacific Index from National Center for Atmospheric Research [NPINCAR]; North Pacific Index from Climate Prediction Center[NPICPC]; Pacific North American Index [PNA]; Arctic Oscillation [AO]; East Pacific Index [EPI]; Alaskan Index [AI] (from Rodionov and Overland 2005).

Changes in biological communities coincide with shifts in regional atmospheric and hydrographic forcing (Grebmeier et al. 2006). As such, other studies of regime shifts have used studies of salmon records (Mantua et al. 1997) to analyze the shifts in locations of salmon fisheries, as regions of the northern Pacific, Bering Sea, and Gulf of Alaska warm up and cool down as a consequence of regime shifts.

It is imperative to consider the regime shifts in the North Pacific as part of the larger context of Arctic and global climate change. The earth climate has experienced dramatic changes in the last 100 years (Intergovernmental Panel on Climate Change [IPCC] 2013). Earth's climate is a sensitive system that exhibits a delicate balance and

interrelationship between the atmosphere and the ocean. Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade with ocean warming accounting for more than 90 percent of the energy accumulated between 1971 and 2010 (IPCC 2013). Arctic sea ice is a key indicator of the state of global climate because of both its sensitivity to warming and its role in amplifying climate change (Maslowski et al. 2012). The main reductions in sea ice have come not only spatially through extent, but thickness as well as measured through in-situ observations and satellite data. The observed rapid loss of thick multiyear sea ice over the past decades and the recent reduction of ice extent in September 2012 to 49 percent of the 1971-2000 climatological mean are inconsistent with model predictions of a nearly sea-ice free Arctic around 2070 and beyond made just a few years ago (Overland and Wang 2013). Accelerated sea ice loss over the last decade have caused scientists to re-evaluate why this dramatic loss in sea ice is occurring and how the sea ice loss is affecting climate in the Arctic, as well as on a global scale (see Figure 2). Many of these re-evaluations have led to revised predictions of an ice free Arctic anywhere between 2030 and 2060 (Wang and Overland 2009, 2012; Massonnet et al. 2012).

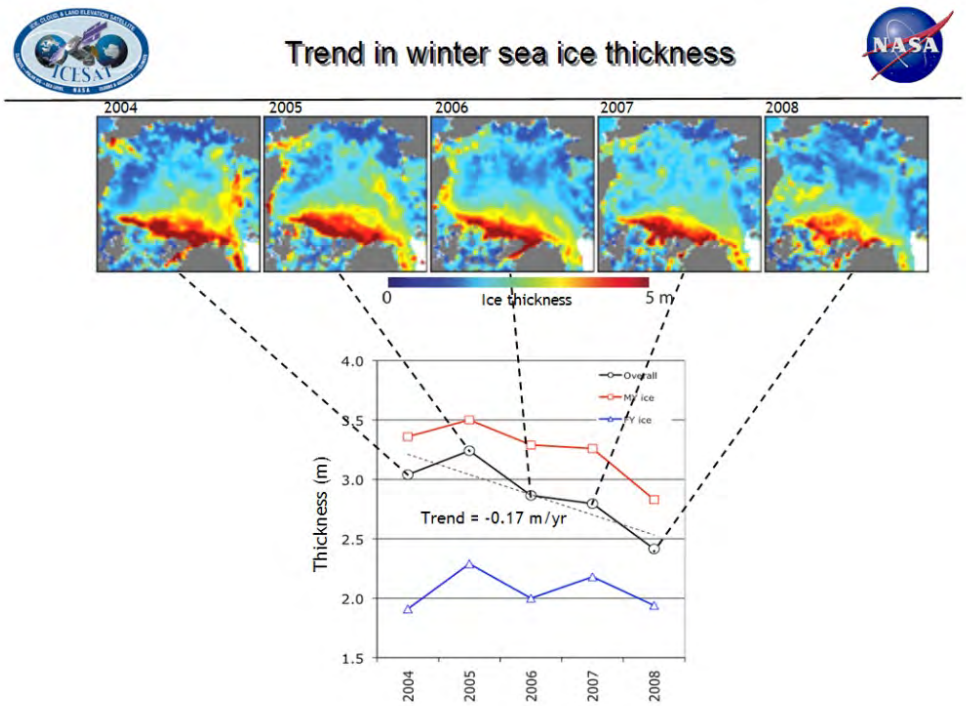

Figure 2. ICESat measurements of the distribution of winter sea ice thickness over the Arctic Ocean between 2004 and 2008, along with the corresponding trends in overall, multi-year and first-year winter ice thickness (from National Aeronautics and Space Administration [NASA]/Jet Propulsion Laboratory [JPL] 2013).

It is important to note that in the North Pacific, extending into the Bering Sea, sea ice is first year ice that melts out each year. Thus trends seen in the Arctic as a whole in terms of ice extent and thickness changes, along with SST changes, do not necessarily coincide with or have similar rates of decline as the changes seen in the North Pacific. A recent study by Frey et al. (2013) found that ice cover in the Bering Sea south of St. Lawrence Island has seen a slight increase from 1979–2008 with slight declines near the Bering Strait. The declines are possibly due to earlier sea ice breakup and later sea ice formation with the increases due to earlier sea ice formation during winter months (Frey et al. 2013). However within that time period, there were fluctuations where sea ice extent in the Bering Sea at its maximum in March was greater from 1989–1998 than 1979–1988 with 1999–2008 having smallest extent out of the three decades, showing that there is significant interannual and decadal variability. Also, for first year ice thickness

there is relatively significant interannual variability with seasonal cycle thickness changing by 0.15m (Frey et al. 2013). The challenge then is to determine what could be causing such variability in the North Pacific.

B. INTENT OF STUDY

While many studies have focused on the processes that occur in the entire pan-Arctic region (e.g., Clement Kinney et al. 2005, 2009, Maslowski et al. 2008, Maslowski et al. 2012), few studies have examined the multi-decadal variability in the northern North Pacific, specifically in the Gulf of Alaska, and the Bering Sea, and its potential effect on the Arctic. The Bering Sea and Gulf of Alaska represent important sub-Arctic regions for the United States as they represent territorial waters for the country. Since the sea ice in these locations is seasonal and melts every summer, they also provide prime research areas to examine regional effects of global climate change.

North Pacific weather and climate patterns have been linked to three large scale indices. They are the Arctic oscillation (AO), Pacific/North American pattern (PNA), and the Pacific decadal oscillation (PDO) (Clement Kinney 2011). The AO is the leading mode of sea level pressure variability in the Northern Hemisphere and represents a circulation pattern in which pressure patterns over the polar regions and the middle latitudes reflect an opposing pattern on time scales ranging from weeks to decades (National Snow and Ice Data Center [NSIDC] 2013). The PNA represents the variability in low-frequency heights across the Pacific (Climate Prediction Center [CPC] 2013). The negative phase of PNA is associated with a westward retraction of the jet stream toward eastern Asia, block activity over the high latitudes of the North Pacific. Positive PNA is associated with anomalous warm temperatures over western Canada as well as high level of precipitation in the Gulf of Alaska (Clement Kinney 2011). The PDO is defined at the leading principal component of North Pacific monthly sea surface temperatures describing the inter-decadal climate variability as a long-lived El Nino like pattern of Pacific climate variability (Hare and Mantua 2000). Fisheries scientist Steven Hare coined the term in the 1990s to help explain the connections between Alaska salmon

production cycles and Pacific climate (Hare et al. 1999). The index describes the detection of warm or cold waters north of 20°N. In the warm/positive phase, the east Pacific becomes warm and the opposite occurs during the cold phase (see Figure 3) (Northwest Fisheries 2013).

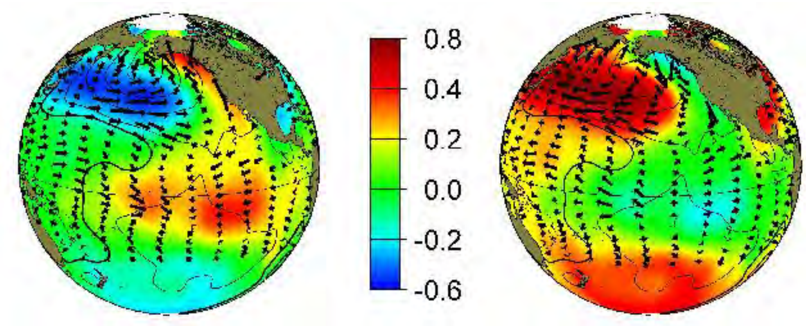

Figure 3. Positive phase PDO (left image) vs. negative phase PDO (right image) (from University of Washington 2013).

Understanding these indices, especially the PDO, is important to potentially identifying climate regime shifts in the northern North Pacific (see Figure 4). Regime shifts are difficult phenomena to analyze accurately and comprehensively due to insufficient data. While a climatic regime may dominate for decades, a shift can occur within a year. Shifts in the pan-Arctic region could have dramatic effects on things such as sea ice cover and position/strength of the Aleutian low. While studies have recognized the occurrence of regime shifts in the subarctic Pacific such as the 1976/1977 and 1988/1989 (Hare and Mantua 2000), there has not been much research as to whether these shifts are represented in global and regional models and how models can help better understand and predict them.

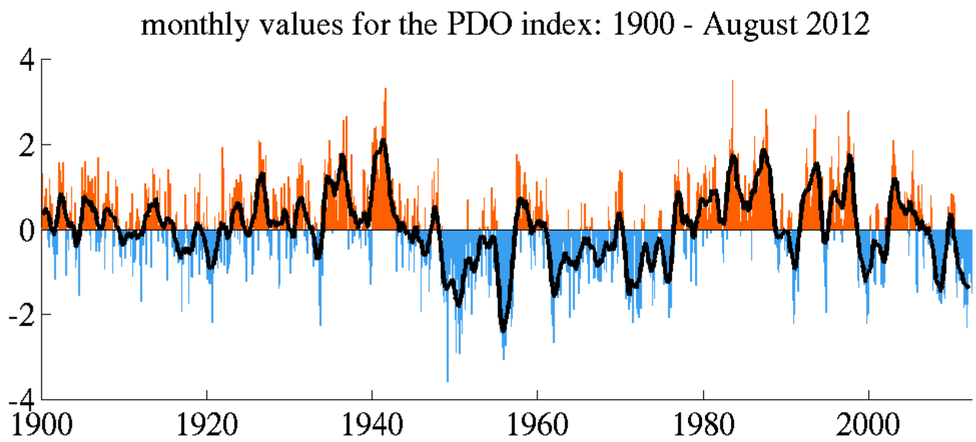

Figure 4. Month values for PDO index from 1900–2012 (from University of Washington 2013).

Global climate models, due to their coarse resolution, cannot accurately represent many physical processes occurring in northern North Pacific and the Bering Sea. In order to properly analyze the regime shifts in the Bering Sea, results from the high-resolution regional arctic system model (RASM) together with available observations and the global climate and Earth system models (GC/ESMs) from Coupled Model Inter-comparison Project Phase 5 (CMIP5) are used. The main goal of this research is to synthesize model results and observations to advance understanding of inter-ocean communication, processes involved and multiple feedbacks between realms (e.g., sea ice, ocean, atmosphere, land) in the Bering Sea at time scales ranging from seasonal to decadal.

C. OVERVIEW

This research involves analyses and synthesis of regional and global climate model results along with available observational data to advance the understanding of critical physical processes associated with the communication between the northern Pacific Ocean and the Arctic Ocean through the Bering Sea. Comparisons will be made between outputs from multiple model runs and historical observations. Results from the RASM will be compared to GC/ESMs from CMIP5. Analyses will focus on changes in sea surface temperatures, air temperatures, ice thickness, ice volume, and upper ocean

heat content and examining correlations to the PDO. These analyses will help to understand the ability of models to capture significant climate regime shifts associated with changes in the PDO to advance understanding of their causality.

This thesis is organized into the following chapters: Chapter II discusses the Navy relevance to climate modeling research in the pan-Arctic, specifically the Bering Sea region; Chapter III describes the model and the data analysis methodology used to conduct this research; Chapter IV presents results from the analysis and synthesis of the model data; Chapter V contains conclusions and makes recommendations for future research.

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II. NAVY RELEVANCE

A. STRATEGIC GUIDANCE

Interest in the Arctic has grown significantly in the last decade due to the accelerating ice melt opening up potential shipping lanes and the discovery of vast deposits of natural resources (see Figure 5). There has already been a 118 percent increase in maritime transit through the Bering Strait since 2008 with over one million tons of cargo transported (U.S. Coast Guard [USCG] 2013). The region has already seen $3.7 billion in investments for offshore oil drilling leases as 13 percent of the world's oil reserves along with 30 percent of the natural gas reserves are believed to be located in the Arctic (USCG 2013). In order to address the United States involvement in the region, numerous guiding documents have been published and subsequently revised. Under the current administration, the *National Security Strategy* (NSS) released in 2010 made only a brief mention regarding the Arctic. The guidance surmised that as an Arctic nation, the country has responsibilities and interests in the region and that we would take the necessary steps to meet our national security needs while protecting the environment and responsibly managing resources in our territorial waters (White House 2010).

Figure 5. Northern Sea Route (Northeast Passage) transit distance versus Suez Canal Route (from Spiegel International 2013).

In the *Quadrennial Defense Review* (QDR) released the same year, the Department of Defense (DoD) expanded on the administration's guidance. Overall the QDR stressed that the DoD must be able to more comprehensively monitor the air and land through domain awareness tools especially in the Arctic (DoD 2010). It also stressed the importance of continued engagement with allies, namely Canada, in the context of regional security and to engage with Russia to seek opportunities to manage Arctic policy issues that will arise in the next several decades (DoD 2010). The most significant conclusion from the QDR pertinent to guidance for the Bering Sea region was the understanding that greater collaboration with the Coast Guard and the Department of Homeland Security (DHS) needs to occur. The opening of the Arctic waters in the decades ahead, which will permit seasonal commerce and transit, presents a unique opportunity to work collaboratively to promote a balanced approach to improving human and environmental security in the region. Issues that will need to be addressed include gaps in Arctic communications, domain awareness, search and rescue, and environmental observation and forecasting capabilities to support both current and future planning and operations (DoD 2010).

Realizing that more specific guidance was required, the Obama administration released *The National Strategy for the Arctic Region* (NSRA) in 2013. This document expands upon the 2010 NSS and QDR and contained three main tenets. The first is to advance United States security interests by enabling our vessels and aircraft to operate in the region. The second is to pursue responsible stewardship to protect the environment and conserve the region's natural resources. The final is to strengthen international cooperation to pursue arrangements that advance collective interests including the United States accession to the United Nations Convention on the Law of the Sea (UNCLOS) (White House 2013).

Through forward thinking leadership, the Navy established a working group in 2009 to address how the Navy would respond to the growing interest in the Arctic. The group was called Task Force Climate Change and its first mandate was to develop the Navy Arctic Roadmap. The Navy Arctic Roadmap provided a chronological list of Navy

action items, objectives, and desired effects for the Arctic region from fiscal year (FY) 10–14. Focus areas included (Task Force Climate Change [TFCC] / Oceanographer of the Navy 2009):

- Strategy, policy, missions, and plans
- Operations and training
- Investments in weapons, platforms, sensors, command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR), installations, and facilities
- Strategic communications and outreach
- Environmental assessment and prediction

The next update to the Arctic Roadmap is due to be released soon. In his prepared statement for an April 16, 2013, hearing before the House Armed Services Committee, Admiral Jonathan Greenert, the Chief of Naval Operations (CNO), stated:

> Emerging projections assess that the Arctic will become passable for shipping several months out of the year within the next decade—about 10 years earlier than predicted in 2009 when we first published our Arctic Roadmap. This will place new demands on our fleet for presence in the Arctic and capabilities to operate in the Arctic environment. Between now and the start of FY2014 we will update our Arctic Roadmap, and accelerate many of the actions Navy will take in preparation for a more accessible Arctic. During FY2014 we will implement this revised roadmap, including developing with the U.S. Coast Guard plans for maintaining presence and search and rescue capability in the Arctic and pursuing exchanges with other Arctic countries to familiarize our Sailors with Arctic operations. (O'Rourke 2013)

The Navy Arctic Roadmap laid the foundation for the Navy to develop strategic objectives it published in 2010. The Navy's desired end state is a safe, stable and secure arctic region where U.S. national and maritime interests are safeguarded and the homeland is protected (CNO 2010). Overall there are five specific objectives for the Navy. They include:

- Contribute to safety, stability, and security in the region.
- Safeguard U.S. maritime interests in the region.
- Protect the American people, our critical infrastructure, and key resources

- Strengthen existing and foster new cooperative relationships in the region
- Ensure Navy forces are capable and ready

These strategic objectives represent the ends and the ways and means are being analyzed and developed with the release of the updated Arctic Roadmap.

The Coast Guard in 2013 also provided a strategic guidance document for operating in the Arctic. The Coast Guard already has a presence in the region with their Seventeenth District based out of Juneau, Alaska (AK). Assets in the region include the icebreakers *Polar Star* and *Polar Sea*, both of which are not fully mission capable. The *Polar Star* recently underwent an extensive refit and was reactivated for service in December 2012 and the Polar Sea is in caretaker status (USCG 2013). Other major vessels in the region include the medium icebreaker *Healy* and cutter *Alex Haley*, which can operate in light ice conditions and are capable of extended time on station. Smaller vessel capabilities include ice-strengthened ocean-going buoy tenders that are capable of operating in light ice. They provide heavy-lift crane capability and deploy small boats, but are not equipped with a flight deck and have limited endurance. Other ships in the Coast Guard's fleet, including the national security cutters and high endurance cutters, are not ice-strengthened, but can operate in open water north of the Arctic Circle for limited periods (USCG 2013).

With these assets, the strategy of the Coast Guard is to ensure safe, secure, and environmentally responsible maritime activity in the Arctic. Maritime domain awareness (MDA) stands as the corner piece that fuses the main principles of the Coast Guard strategy. They are advocating for the establishment of an interagency Arctic Fusion Center that promotes cooperation and coordination, and employs joint, interagency, and international capabilities to enable sustainable development and environmental protection. Part of that MDA requires effective maritime presence to ensure safe, secure, and environmentally responsible maritime activity. Presence also enables the Coast Guard to respond to vessels in distress, save lives, prevent attacks, and protect against pollution. Effective presence requires the right assets and capabilities to be in the right places at the right times. An integrated surface and air presence will yield critical, real-time information and enhanced MDA on vessels transiting and operating in the region.

Setting requirements that seek an adaptable mix of cutters, boats, aircraft (including unmanned aerial systems), and shore infrastructure to enable effective seasonal operations. Conduct operations, training, and familiarization activities including Operation Arctic Shield and regional domain awareness flights tie together the overall strategy of the Coast Guard (USCG 2013).

B. NAVY CAPABILITIES

The Navy has a stake and interest in the Arctic for many reasons. Two of the most important are the increasing maritime activity and energy security due to discovery of natural resources (Task Force Climate Change [TFCC] / Oceanographer of the Navy 2009). Other major interests include sea level rise impact on current installations and potential increase in humanitarian assistance and disaster response in the region.

With the release of the NSS and the QDR, in 2011, Congress commissioned the DoD to develop a report on Arctic operations addressing strategic national security objectives, needed mission capabilities, an assessment of changing the *Unified Command Plan* (UCP), needed basing infrastructure, and the status of and need for icebreakers (DoD 2011). Specifically the report detailed the capabilities needed to support identified strategic objectives, any identified gaps, and what the mitigation approaches are to address them. It also assessed the advantages and disadvantages of amending the UCP to designate a single combatant commander for the Arctic region, basing infrastructure needed to support the identified strategic objectives, including the need for a U.S. deep-water port in the Arctic, and the status of and need for icebreakers, not necessarily in the DoD or the Navy, in the context of the capabilities to support national security objectives (DoD 2011).

Specific to the Navy, the DoD capabilities report discussed how the Navy's surface ships are not ice-strengthened and therefore not suitable for operations in first year ice or even in the marginal ice zone (MIZ). The submarine force has been operating in the Arctic since 1958 and conducts a bi-annual exercise in the Arctic to validate submerged operations and tactics in the Arctic environment. Operational Arctic environmental support is provided by the Naval Ice Center in Suitland, Maryland. The

center provides sea ice analysis and forecasting for the polar regions primarily in support of the submarine fleet but also in support of other national missions. The Naval Ice Center, which is part of the tri-agency National Ice Center, is a model for interagency cooperation with National Oceanic and Atmospheric Administration (NOAA) and the Coast Guard, and a vital supporting capability for any current and future Arctic operations (DoD 2011).

The Navy conducted its own internal assessment of the missions that it needs to be able to perform in the Arctic in the future assessing these requirements for the near- (2010–2020), mid- (2020–2030), and far-term (beyond 2030). Potential capability gaps in these missions were analyzed in detail and published in the Navy's Arctic *Capabilities Based Assessment* (CBA) (DoD 2011). The CBA found gaps that consisted of an inability in the Arctic to fully:

- Provide environmental information
- Maneuver safely on sea surface
- Conduct training, exercise, education
- Maneuver safely in air
- Sustain the force
- Establish lines of communication
- Provide reliable high data rate communication
- Provide accurate navigation information
- Maneuver safely or quickly on ground (including ice-covered ground)
- Operate kinetic weapons
- Collect required intelligence
- Disrupt enemy weapon systems

Of special note for addressing the first gap listed, to provide environmental information, the United States Navy (USN) desired effect would be—to provide meteorology and oceanography (METOC) information within the same standards as those applied to traditional areas of responsibility (AORs), plus provide ice reports detailing position, thickness, movement, and expected short-term and long-term change. While the Naval Ice Center currently provides the ice support, it is not always real time

and coordination is still being implemented with the Fleet weather centers. The insufficient ability to provide METOC information, to include timely ice reports and accurate navigational charts, is not unique to the USN, but common to civilian and foreign militaries as well, due to underlying gaps in the collect, analyze, forecast, and exploit chain of events (Mills 2012).

Overall, the DoD capabilities report found that current posture in the Arctic region is adequate to meet near- to mid-term U.S. defense needs. However, the United States needs assured Arctic access to support national interests in the Arctic. This access can be provided by a variety of proven capabilities, including submarines and aircraft, but only U.S.-flagged ice-capable ships provide visible U.S. sovereign maritime presence throughout the Arctic region while also providing MDA (DoD 2011).

The challenge for maintaining and developing the capabilities for accomplishing the strategic objectives set forth by higher guidance is to balance the risk of being late-to-need with that of making premature Arctic investments. The U.S. government must monitor and reevaluate the changing environmental and geo-political landscape in the Arctic region to address capability gaps in order to be prepared to operate in a more accessible Arctic. Key challenges include: shortfalls in ice and weather reporting and forecasting; limitations in C4ISR due to lack of assets combined with harsh environmental conditions and timely knowledge about their state and change; limited inventory of ice-capable vessels; and limited shore-based infrastructure. The key will be to address needs in step with the rate at which activity in the Arctic increases and balance potential investments in these capabilities with other national priorities (DoD 2011).

Since the Coast Guard and Navy will overlap and share responsibility in the Arctic, it is necessary to address the Coast Guard's capabilities and potential shortfalls as well. Numerous studies have examined Coast Guard shortfalls in the Arctic, from the need for additional icebreakers and long-range patrol vessels to improved communications and maritime domain awareness capabilities and aviation assets. There is no obvious or easy way to close these gaps. The biggest challenge for the Coast Guard is their limited icebreaking capability. The United States must plan for ice capable assets

that can effectively carry out year-round search and rescue, environmental response, charting, scientific research, and other Arctic operations to meet overarching strategic objectives (USCG 2013).

III. MODEL DESCRIPTION AND METHODS

A. MODEL DESCRIPTION

This study has conducted analyses comparing results from the community climate system model version 4 (CCSM4) developed by the University Corporation for Atmospheric Research (UCAR) with those from RASM and from observations. The compared field between the two models was sea surface temperatures (SST) between 1970 and 2005. RASM is a multi-institutional modeling effort let by the Naval Postgraduate School. RASM results were compared to historical observational SST data in the Gulf of Alaska, Bering Sea, and North Pacific.

1. CCSM4

The CCSM4 version of the model, which is supported primarily by the National Science Foundation (NSF) and the U.S. Department of Energy (DoE), was publicly released on April 1, 2010. CCSM4 simulation results were used in the IPCCs fifth scientific assessment report. The model comprises of five constituents: atmosphere, ocean, land-surface, sea-ice, and a coupler. It has a hub-and-spokes architecture in which all coupling data traffic from/to the models is routed via the coupler, which performs regridding and flux calculations as well as assures mass, energy and property conservation. All of the major components of CCSM4 have been significantly improved from the previous versions. Some of the major improved capabilities include: an improved portrayal of deep convection, the ability to depict transient changes in land cover, a new scheme for tracking melt ponds atop sea ice, and a new scheme for parameterizing ocean overflows (UCAR 2013).

Some research has already been done in comparing CCSM4 to reanalysis data and regional ASMs to find inconsistencies with the model. Gent et al. (2011) showed major circulation biases as compared with European Center for Medium range Weather Forecasting (ECMWF) 40-year reanalysis data. Maslowski et al. (2012) found persistent biases in the mean sea level pressure over the central Arctic and differences in ice thickness between 1997 and 2003 for two ensemble runs from CCSM4, one of the best

CMIP5 models at simulating sea ice extent (see Figure 6). Neither of the ensemble runs from CCSM4 showed the overall thinning of sea ice throughout the Arctic as the regional NPS model did and limited observations suggest. A clear decline in thickness of up to 1.5 m is present during March and up to 2 m during September in the NPS model. CCSM4 results show only some spotty, local thinning in the Canadian Arctic Archipelago and the eastern Arctic (Maslowski et al. 2012).

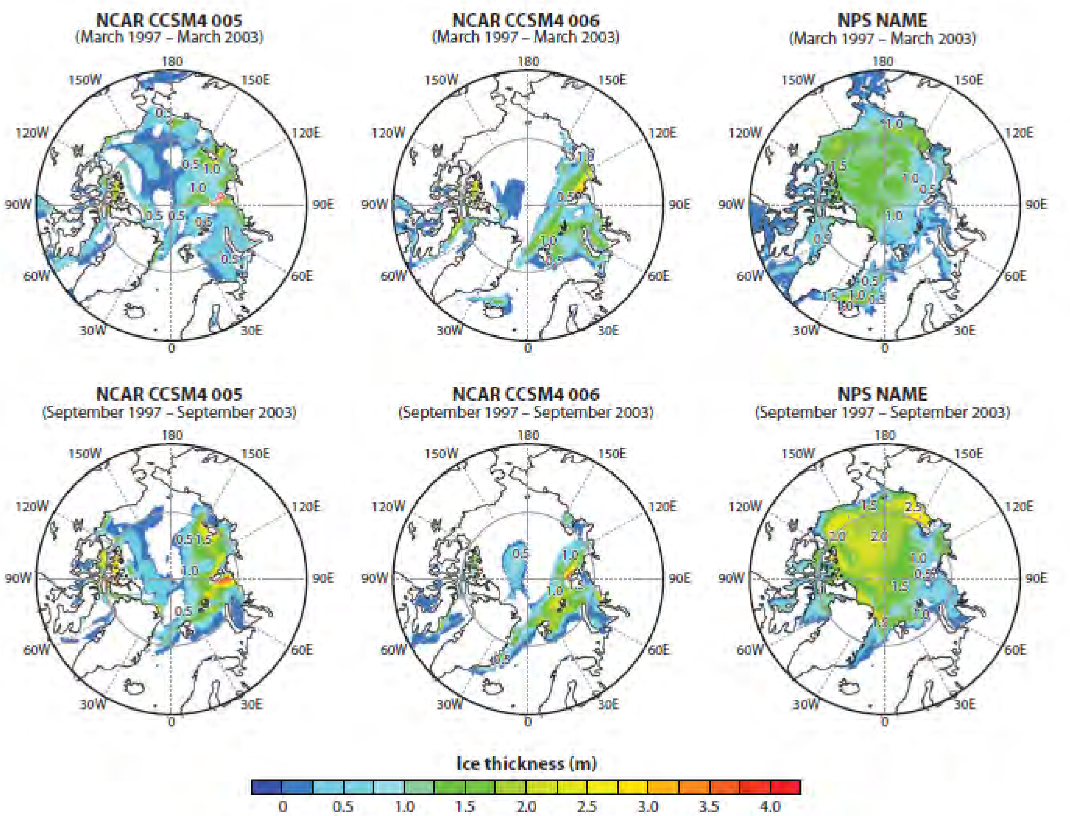

Figure 6. Sea ice thickness (m) differences between 1997 and 2003 during March and September. CCSM b40.20th.track1.1deg.005 (left column), CCSM b40.20th.track1.1deg.005 (center column), NAME (right column) (from Maslowski et al. 2012).

2. RASM

GC/ESMs are limited in realistic simulation of the Arctic climate system due to missing physical mesoscale processes and air-sea-ice feedbacks, which are not realistically, or at all, represented in coarse resolution global models. RASM was

developed to facilitate focused regional studies of the Arctic climate system. Its goal is to improve representation of local physical processes and feedbacks through high resolution atmosphere, ocean, sea/land ice, and land components. Planned improvements in RASM from its predecessor the Regional Arctic Climate (RACM) are addition of model components for ice sheets, ice caps, mountain glaciers, and dynamic vegetation (Maslowski et al. 2012).

The RASM model domain encompasses the entire pan-Arctic region to include the Seas of Japan and Okhotsk in the west, the sub-Arctic North Pacific and North Atlantic Oceans, and the Nordic Seas in the east. This domain includes all major oceanic inflow and outflow regions of the Arctic Ocean, and all of the seasonally ice-covered seas in the Northern Hemisphere. The atmosphere and land models are extended to include all terrestrial drainage basins that bring freshwater to the Arctic (Maslowski et al. 2012). The ocean and sea ice models are regional versions of those used in the NCAR community Earth system model (CESM): the Los Alamos National Laboratory (LANL) Parallel Ocean Program (POP) and Los Alamos (CICE). Land surface processes and hydrology are represented by the Variable Infiltration Capacity model (VIC). The community ice sheet model (CISM) was coupled via CPL7, which is the same as the one in CCSM4. RASM output analyzed for this research was from a compset model version where the sea ice and ocean coupled model that was forced with Common Ocean—Ice Reference Experiments (CORE) II atmospheric fields. The CORE II forcing has air-sea fluxes that are derived from bulk formulae and applied to atmospheric state fields from multiple sources together with a merged Hadley-OI SST product at monthly resolution. The primary atmospheric input data are based on NCEP reanalyzes at 6-hourly resolution. In addition, satellite-based radiation, precipitation, and sea ice concentration are used, at temporal resolutions from daily to monthly. Some of the input data have been adjusted to agree in the mean with a variety of more reliable satellite and in situ measurements that on their own are either too short in duration or too regional in coverage (UCAR 2013). Fluxes have been temporally averaged as needed for distribution as monthly means. The RASM ocean and sea ice models use a horizontal grid spacing of 1/12 º (~9 km) (see Figure 7).

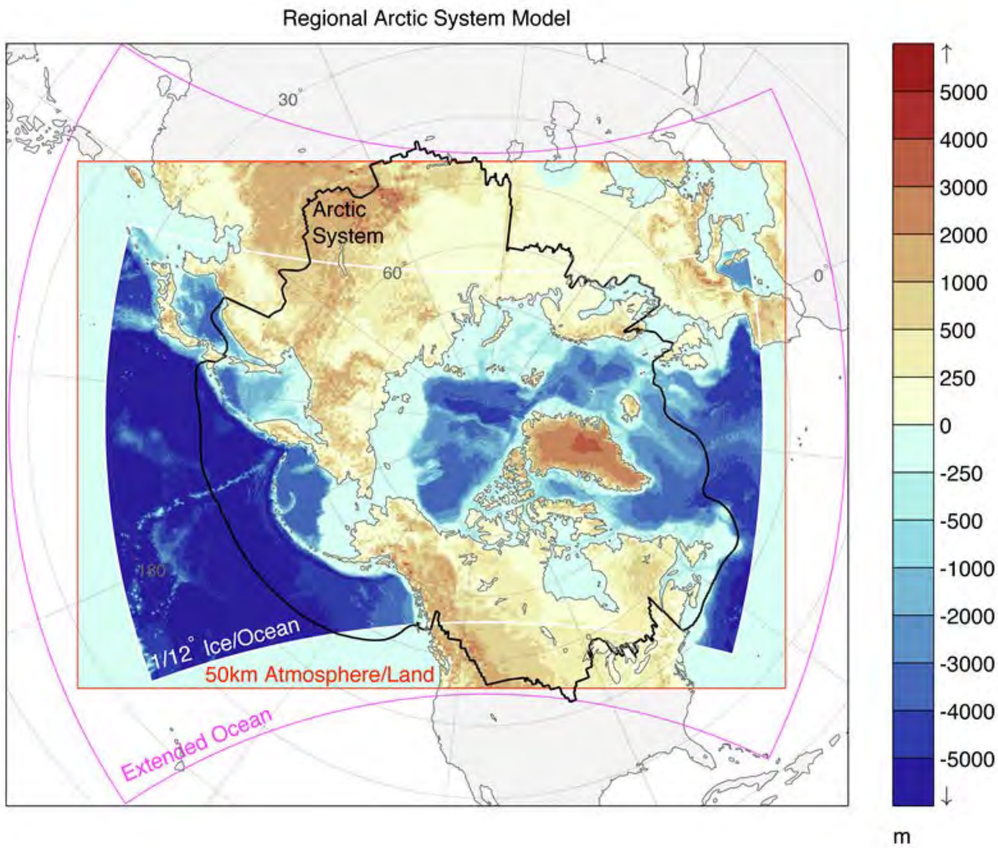

Figure 7. RASM pan-Arctic model domain in the entire colored region. POP and CICE domains are bound by the inner red rectangle. Arctic System domain is bound by the black line (from Roberts 2013).

Two different runs of RASM were analyzed for this study. The first, which going forward will be known as H1 case (H_NC2_58_07_swC2_AL7_CP1_ST1_FR1), had increased albedo for ice, snow, and melt ponds and decreased ice roughness and ice strength compared to the default model values. H1 case ran from 1958-2007. The second case, which going forward will be known as H2 case (H_NC2_48_09_swC2_AL7_CP35c_STm3_FR1_ic_RS6_loop2), had the default ice, snow, and melt pond albedos along with decreased ice roughness compared to the default value, but larger roughness than the H1 case. It also had an increased ice/ocean coupling by drag coefficient and ice strength compared to the default value. H2 case ran from 1948-2009 (R. Osinski, personal communication, October 11, 2013).

B. RESEARCH METHODS

RASM output is written in standard netCDF format. Research for this study was conducted with a MATLAB toolbox developed by the NAME group at NPS designed to analyze RASM model output. The toolkit was used to conduct numerical and statistical analyses as well as creating graphical outputs. Data analyses included the development of time series of full data sets of oceanographic/atmospheric field anomalies through removal of the mean annual cycle. Correlations of RASM data and observational data to the PDO were conducted for both all months and for seasonal only correlations. Correlations were calculated in MATLAB using Pearson's correlation coefficients with P values. The correlation coefficient is a number between -1 and 1. The p-value is the probability of obtaining a test statistic where the null hypothesis is assumed to be true. If the probability is lower than five percent, conventional probability while conducting statistical analysis, the correlation coefficient is considered statistically significant at 95 percent (Sigler 2008). The last statistical analyses conducted were lag correlations. The lag correlations took two time series shifted in time +/- 50 months to study if one time series was a delayed response to another time series.

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IV. RESULTS AND DISCUSSION

A. RASM CLIMATE REGIME SHIFT DETECTION

The starting point for this study was to compare model results to observationally based findings of regime shifts in the North Pacific / Bering Sea by Hare and Mantua (2000). Observations were collected at 31 locations, and from these, Hare and Mantua (2000) developed a graphic of SST changes across regime shifts for 1977, 1989, and 1997. Model analyses include time series of atmospheric and ocean parameters throughout the Bering Sea and Northern North Pacific for 1948–2009.

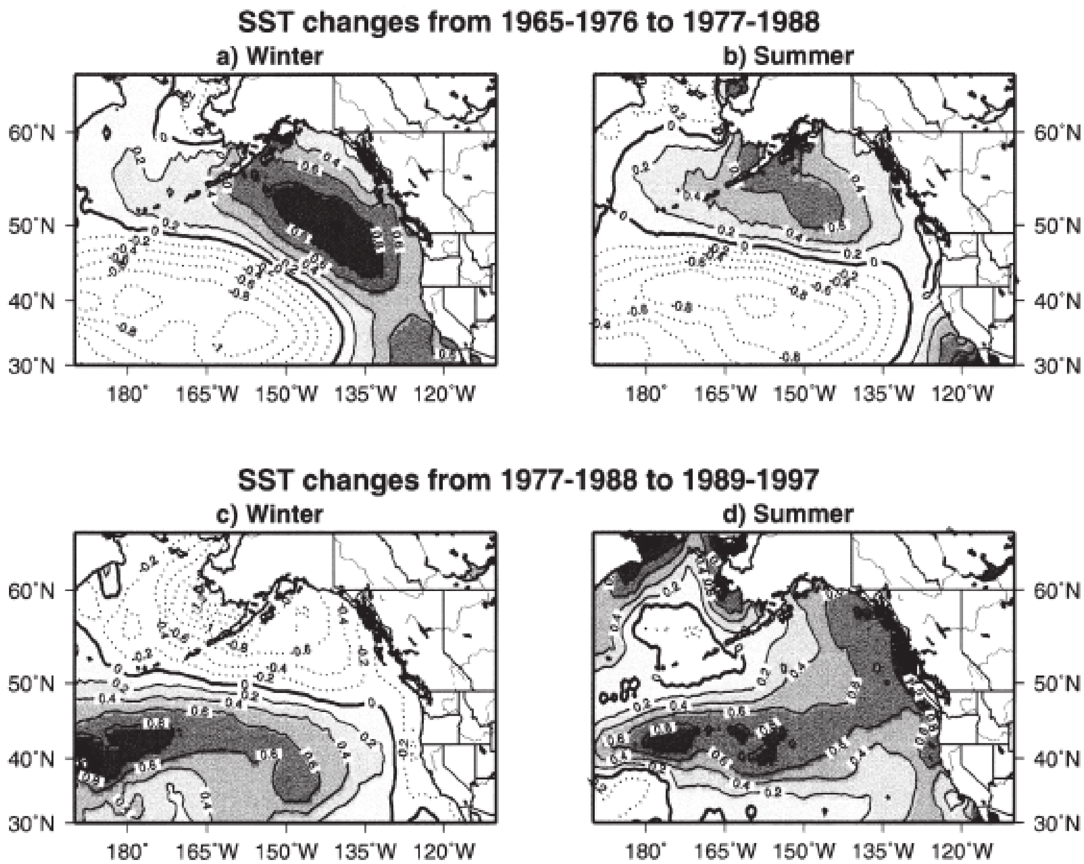

Figure 8. Difference seasonal maps for SST change across 1977 and 1989 regime shifts up to 1997 regime shift (from Hare and Mantua 2000).

Figures 9 and 10 show RASM H1 and H2 case run results simulating SST differences across the regime shifts as in Hare and Mantua (2000). These figures were created taking model monthly averaged SSTs and averaging those over the periods from 1965–1976, 1977–1988, and 1989–1997 and then taking the difference of those averages to obtain the SST changes across the regime shifts.

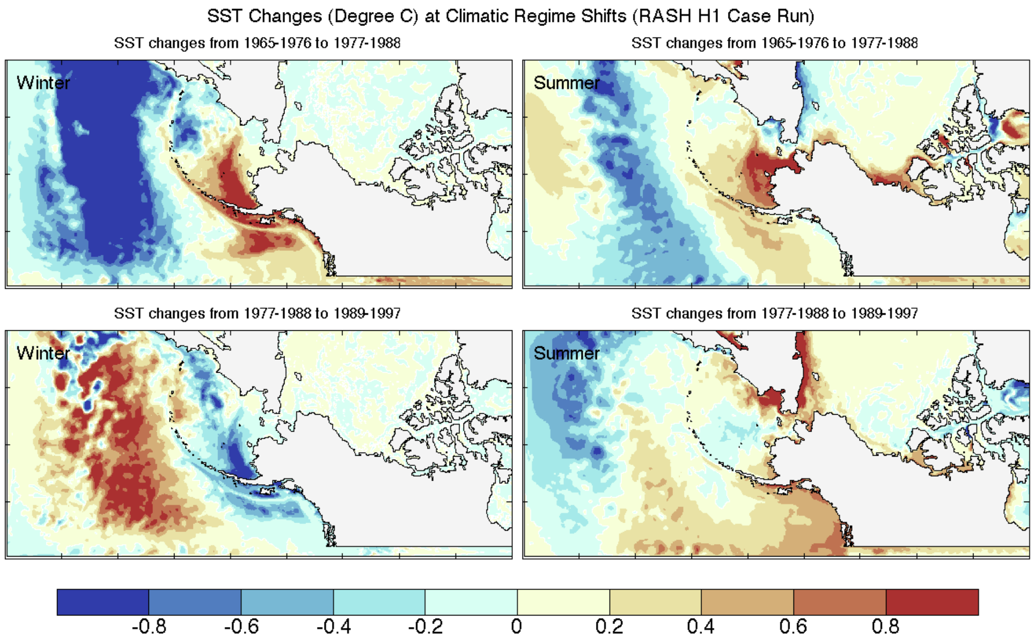

Figure 9. RASM H1 case run winter (left) and summer (right) SST change across 1977 (top) and 1989 (bottom) regime shifts up to 1997 regime shift.

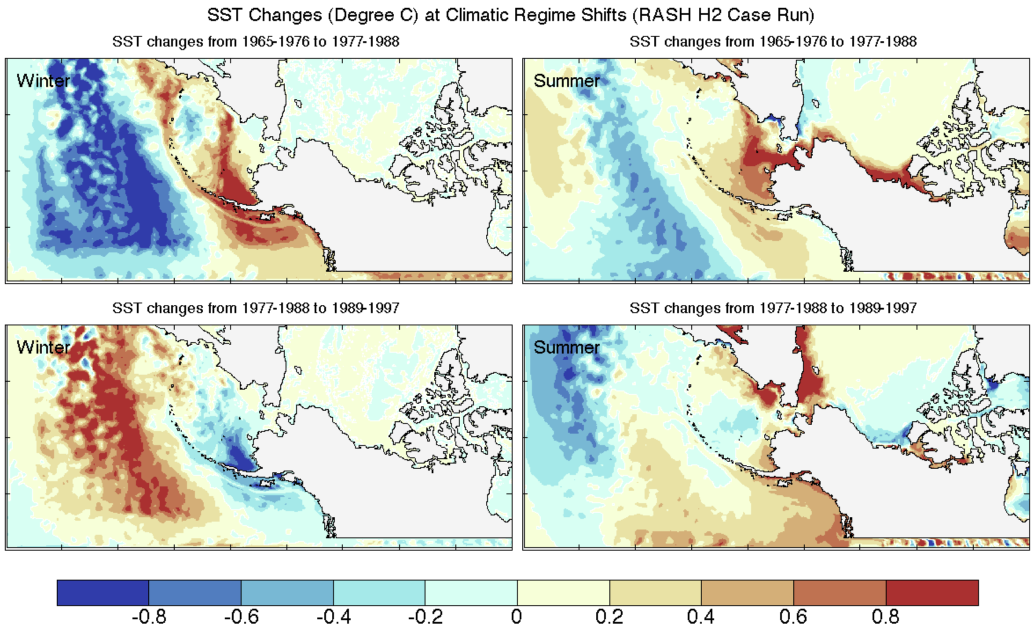

Figure 10. RASM H2 case run winter (left) and summer (right) SST change across 1977 (top) and 1989 (bottom) regime shifts up to 1997 regime shift.

SST changes across the regime shifts are strongest in the winter for both cases. Both cases compare well to the results from Hare and Mantua (2000) in Figure 8. The southeast Bering Sea and Gulf of Alaska during the winter and summer saw overall SST increase with maximum changes near 1ºC for the periods from 1965–1976 to 1977–1988. The northern Pacific Ocean during the same period was much cooler with maximum changes near 1ºC as well. Between 1977–1988 and 1989–1997 there was a reverse between the positive and negative SST changes in the northern Pacific Ocean versus the Bering Sea and Gulf of Alaska that was most prominent during the winter. During the summer there is a shift from positive temperature anomalies in the central Bering Sea to negative temperature anomalies. The reverse holds true for the northern Pacific Ocean with negative temperature anomalies becoming positive. Overall these dramatic temperature shifts provide clear evidence to a regime change occurring in the region.

The next step was to examine the CORE II air temperature forcing across the regime shifts as well as the ice thickness change to determine if the forcing produced accurate SST changes and if those temperature changes caused ice thickness to increase/decrease respectively.

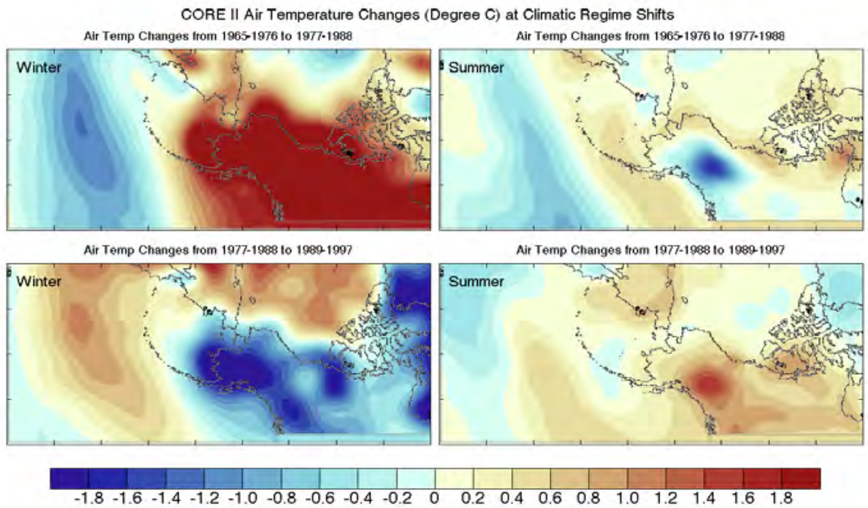

Figure 11. CORE II air temperature changes winter (left) and summer (right) across 1977 (top) and 1989 (bottom) regime shifts up to 1997 regime shift.

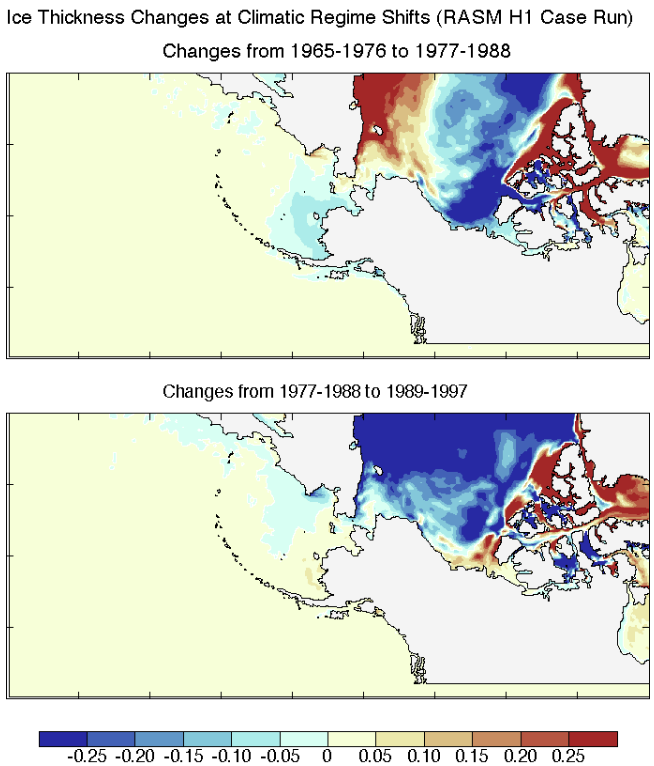

Figure 12. H1 case run sea ice thickness changes across 1977 (top) and 1989 (bottom) regime shifts up to 1997 regime shift.

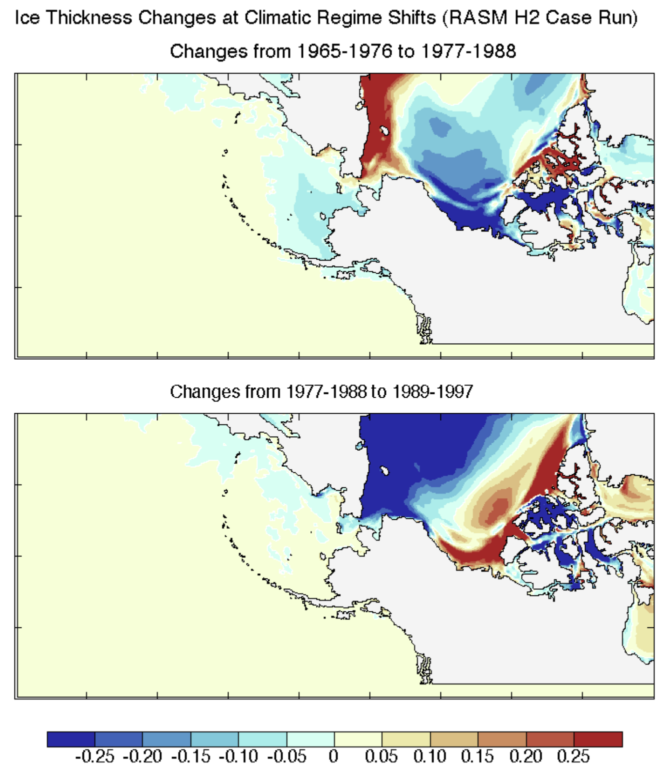

Figure 13. H2 case run sea ice thickness changes across 1977 (top) and 1989 (bottom) regime shifts up to 1997 regime shift.

The CORE II forcing areas for positive and negative air temperature anomalies in Figure 11 across the northern Pacific Ocean, Bering Sea, and Gulf of Alaska correspond closely to the temperature anomalies represented in the H1 and H2 case runs for RASM. During the cold season with sea ice present in the Bering Sea, which was defined as the months of November through June, sea ice thickness decreased with increases in SST and air temperature and increased for decreases in SST and air temperature for both the H1 and H2 case runs (see Figures 12 and 13). For the period of 1965–1976 to 1977–1988 sea ice was 0.05m thicker in the western Bering Sea and 0.10m thinner in the eastern Bering Sea. In the western Bering Sea, sea ice thickness was 0.05m thinner for the period of 1977–1988 to 1989–1997 and 0.05m thicker in the eastern Bering Sea. The absolute magnitude of these changes is small; however, they are significant given the modeled mean thickness of seasonal sea ice in the Bering Sea in the range of 0.30–0.35m (Frey et al. 2013).

To further investigate RASM simulated regime shifts, three areas that showed the greatest SST changes were inspected more closely. The three areas chosen represented the northern Pacific Ocean, southeast Bering Sea, and Gulf of Alaska. A box with bounds between 39º–44ºN and 170ºE–175ºW was examined in the northern Pacific Ocean, 49º–55ºN and 152º–140ºW for the Gulf of Alaska, and 58º–62ºN and 170º–158ºW for the southeast Bering Sea.

In Figures 14 and 15 between 1977 and 1989 the running means and times series of monthly mean SST anomalies for the Gulf of Alaska and southeast Bering Sea indicate most years have positive temperature anomalies during that period. This is consistent with the spatial representation of SST changes examined in Figures 9 and 10. In the northern Pacific Ocean, identification of the climate regime shifts through SST anomalies is not as evident.

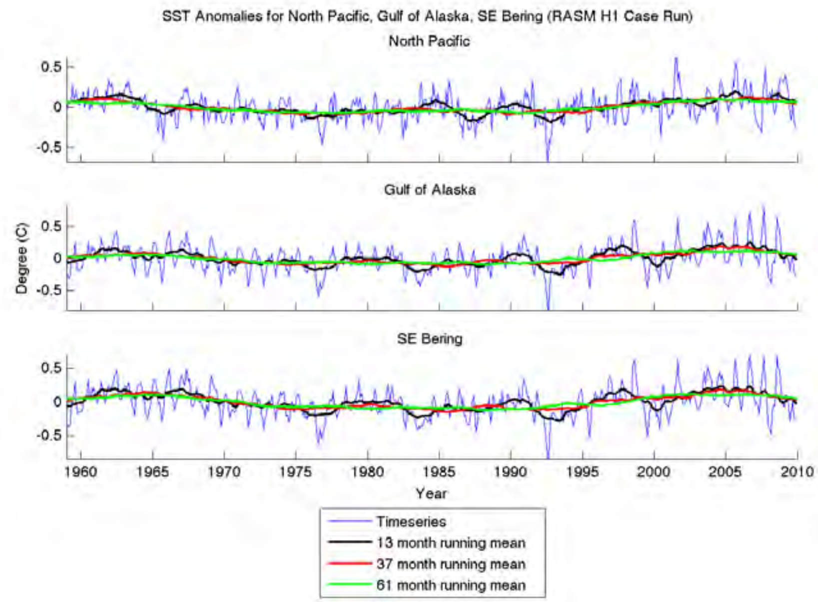

Figure 14. H1 case run SST monthly mean anomalies for the northern Pacific Ocean (top), Gulf of Alaska (middle), and southeast Bering Sea (bottom) with 13, 37, and 61 month running means from 1959–2009.

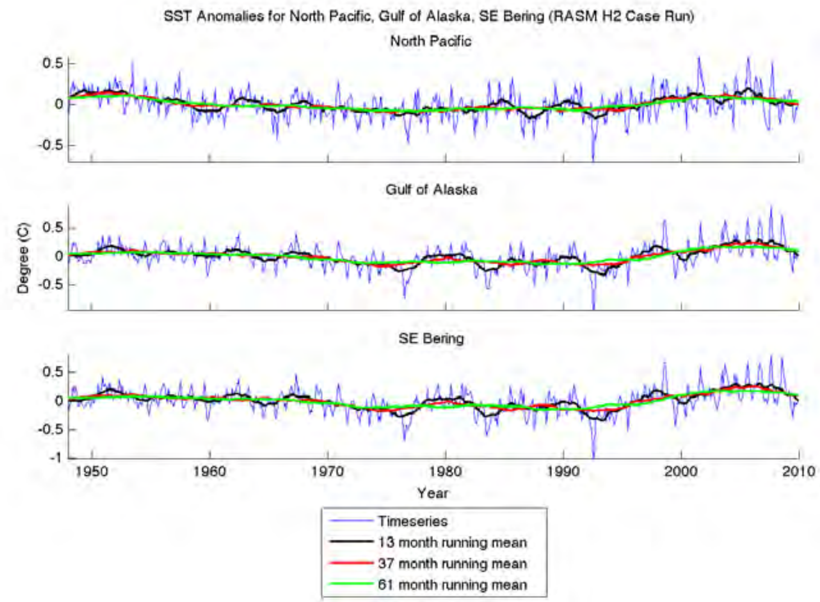

Figure 15. H2 case run SST monthly mean anomalies for the northern Pacific Ocean (top), Gulf of Alaska (middle), and southeast Bering Sea (bottom) with 13, 37, and 61 month running means from 1948–2009.

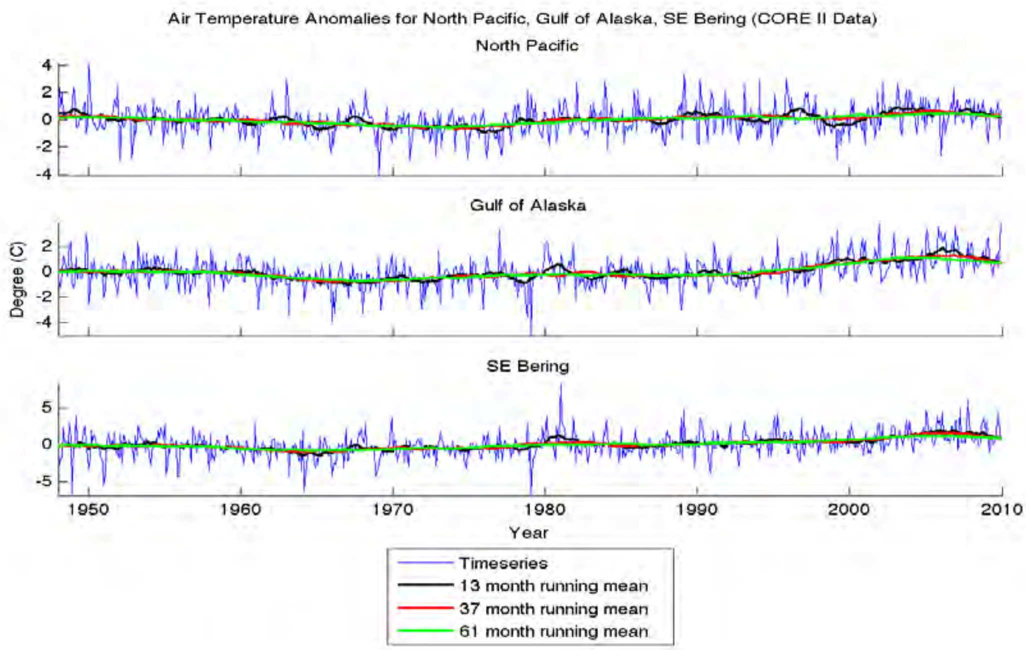

Figure 16. CORE II air temperature monthly mean anomalies for the northern Pacific Ocean (top), Gulf of Alaska (middle), and southeast Bering Sea (bottom) with 13, 37, and 61 month running means from 1948–2009.

Figure 16 shows the CORE II air temperature monthly mean time series anomalies and running means for the same areas. Around 1978, there is a dramatic negative air temperature anomaly in both the Gulf of Alaska and southeast Bering Sea. This corresponds to the overall negative temperature anomalies represented in Figures 9 and 10. In the northern Pacific Ocean, the response to the regime shift is inverse to the changes in the Bering Sea and Gulf of Alaska. Around 1977 and 1989 there is a positive temperature change vice the negative temperature change in the other regions. However, in 1997 the negative shift in the Bering Sea occurs with the negative shift in the Gulf of Alaska.

To obtain a better understanding of the overall structure of the ocean during the regime shifts, an analysis of the heat content of the upper ocean down to 120m was conducted in the same three regions. Included in the analysis were ice thickness changes in the southeast Bering Sea only, as there is no sea ice formation in the Gulf of Alaska or

the northern Pacific Ocean. In Figures 17 and 18, the H2 case run appears to do a better job at identifying the climate regime shifts at 1977, 1989, and 1997. The H1 case run shows the changes for 1977 and 1989 well but not at the same magnitude as the H1 case run. The running means also show a nice oscillating pattern in and out of the regimes. In Figures 19 and 20, the climate regime shifts in the Gulf of Alaska are not as apparent in the time series with abrupt changes at 1977, 1989, and 1997 yet the oscillating wave pattern within the running means shows changes from positive to negative phases around the time of the documented regime shifts. Finally in Figures 21 and 22, the climate regime shift for both model runs show the 1977 change extremely well in the monthly mean time series and the running means. The 1989 shift is not apparent but the 1997 change does appear in the time series and running means, just not as strongly as the 1977 shift. Ice thickness changes correspond to seeing decreases in ice thickness with increases in heat content and vice versa.

Having identified modeled climate regime shifts with SSTs and heat content at 0–120 m, the next step of the study was to understand how RASM represents water properties in the upper ocean. Vertical profiles were produced for the H1 case run from 1959–2009 and the H2 case run from 1948–2009. The profiles consist of monthly averages of temperature, salinity, and density. Examining the differences between the profiles in the two runs, the H1 case is warmer than the H2 case in the northern Pacific Ocean (Figure 23) though the difference between the two becomes significantly smaller between July and December. Salinity values (Figure 24) are lower for the H1 case for all months making the H1 case less dense (Figure 26). For the Gulf of Alaska, both the H1 and H2 case runs temperatures are nearly identical between April and December, with the H1 case being slightly cooler near the surface causing a steeper temperature gradient between January and March (Figure 27). Salinity values are nearly identical for both cases between July and December with the H1 case values being slightly less than the H2 case above the halocline (region in the vertical structure of the ocean with an abrupt change in salinity with depth) between January and June (Figure 28). Overall the density profiles for the Gulf of Alaska are nearly identical as the slight variations in temperature and salinity become negligible (Figure 28). Finally for the southeast Bering Sea, the H2

case is slightly warmer than the H1 case at all vertical levels (Figure 29) though the difference is almost negligible in the months of July through December. Salinity values are lower for H2 than H1 for all months throughout the column (Figure 30). Density values are thus lower for the H2 case than the H1 case. Next section compares model profiles with observations at GAK1, a long–term oceanographic station in the Gulf of Alaska, to get a better understanding of model skill in representing upper ocean hydrography.

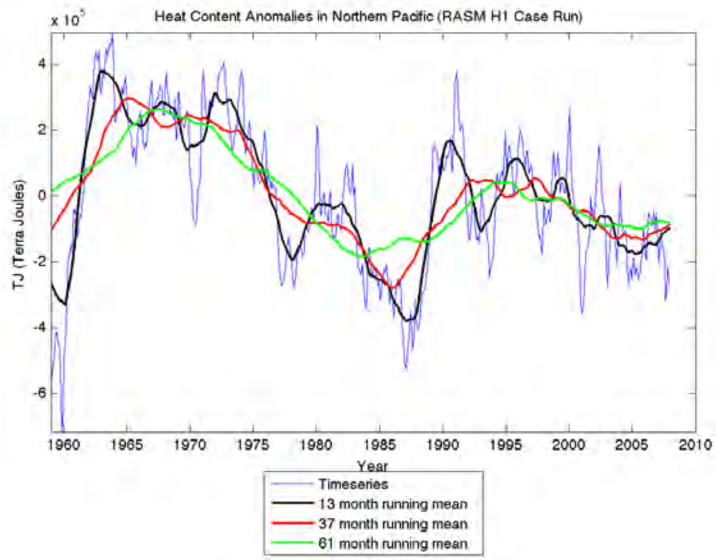

Figure 17. H1 case run monthly mean heat content anomalies with 13, 37, and 61 month running means in the northern Pacific Ocean from 1959–2007.

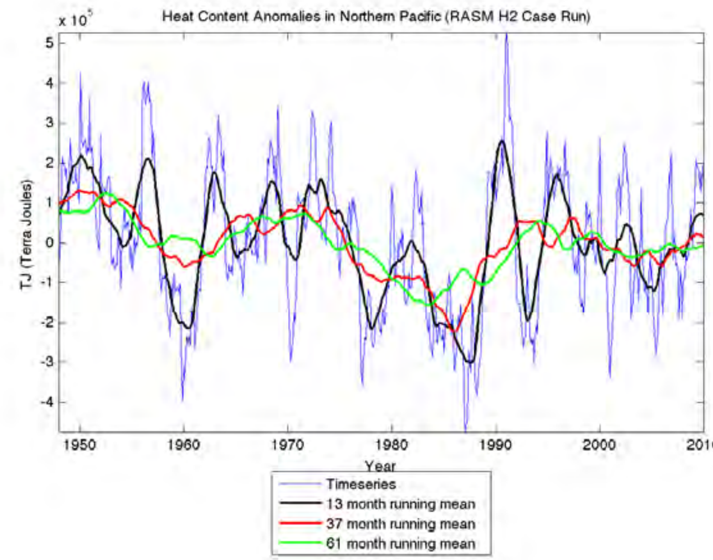

Figure 18. H2 case run monthly mean heat content anomalies with 13, 37, and 61 month running means in the northern Pacific Ocean from 1948–2009.

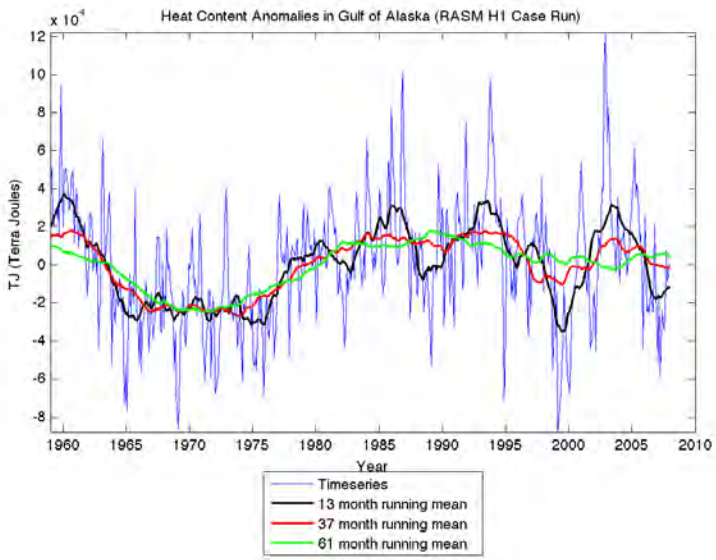

Figure 19. H1 case run monthly mean heat content anomalies with 13, 37, and 61 month running means in the Gulf of Alaska from 1959–2007.

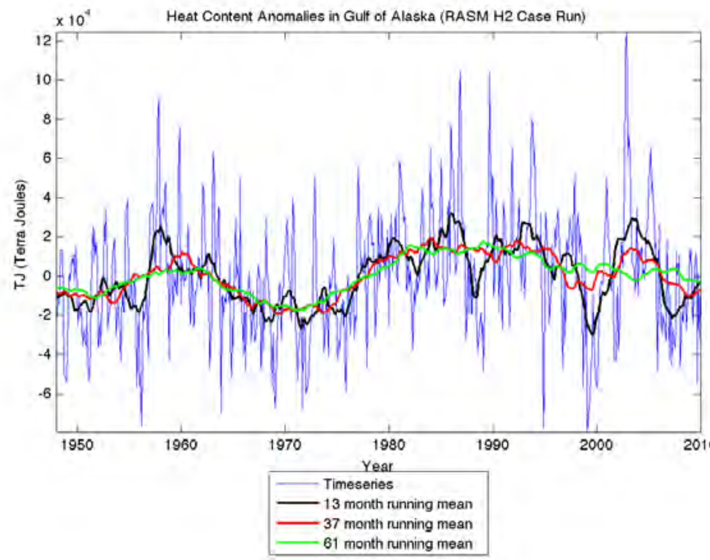

Figure 20. H2 case run monthly mean heat content anomalies with 13, 37, and 61 month running means in Gulf of Alaska from 1948–2009.

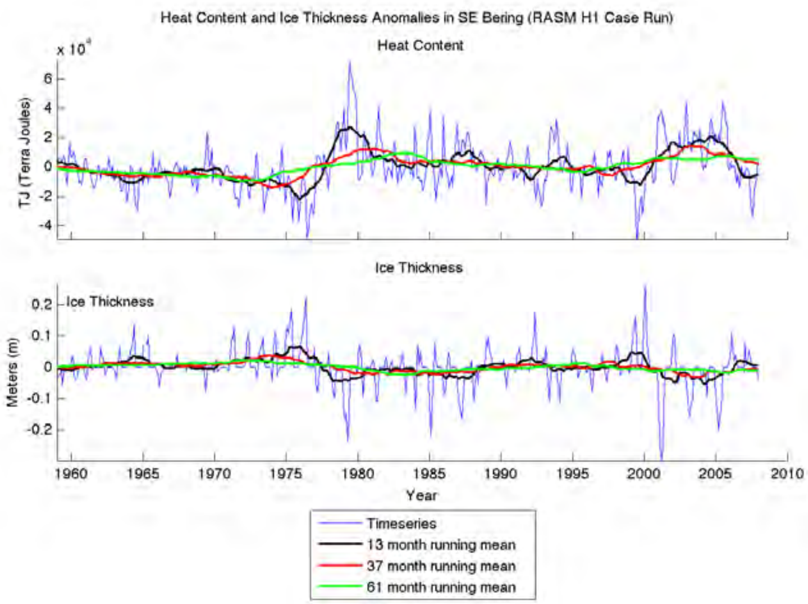

Figure 21. H1 case run monthly mean heat content and ice thickness anomalies with 13, 37, and 61 month running means in the southeast Bering Sea from 1959–2007.

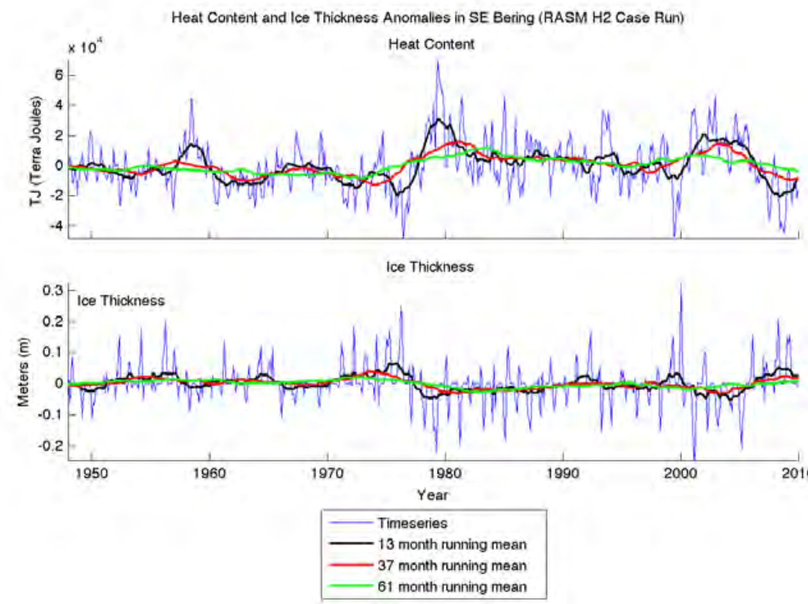

Figure 22. H2 case run monthly mean heat content and ice thickness anomalies with 13, 37, and 61 month running means in the southeast Bering Sea from 1948–2009.

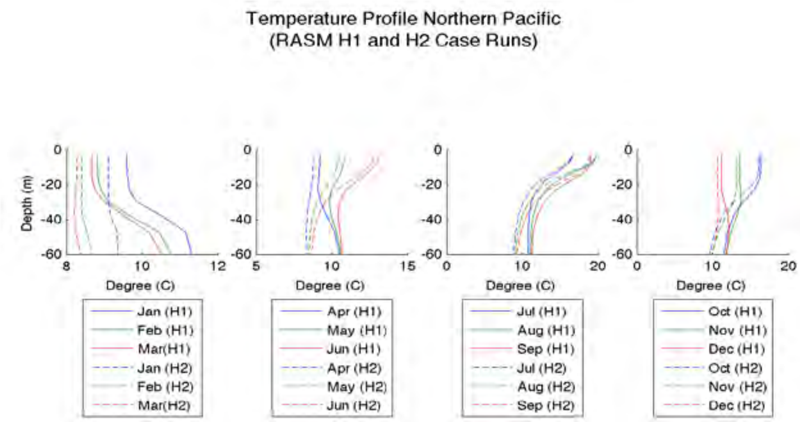

Figure 23. H1 and H2 case runs of monthly mean temperature profiles northern Pacific Ocean 1959–2009 and 1948–2009.

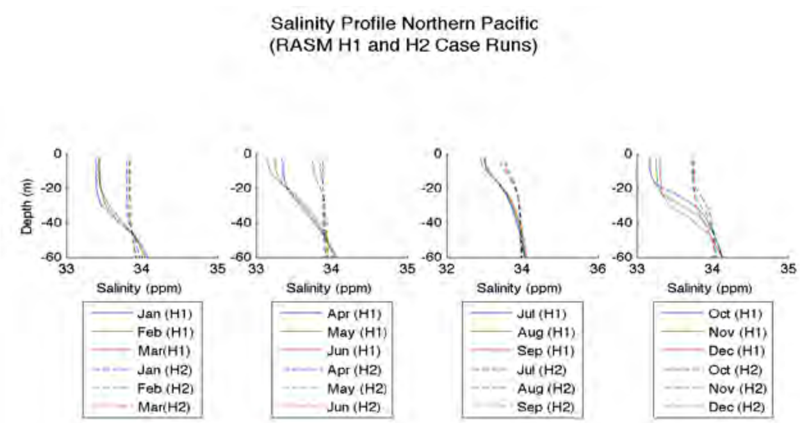

Figure 24. H1 and H2 case runs of monthly mean salinity profiles northern Pacific Ocean 1959–2009 and 1948–2009.

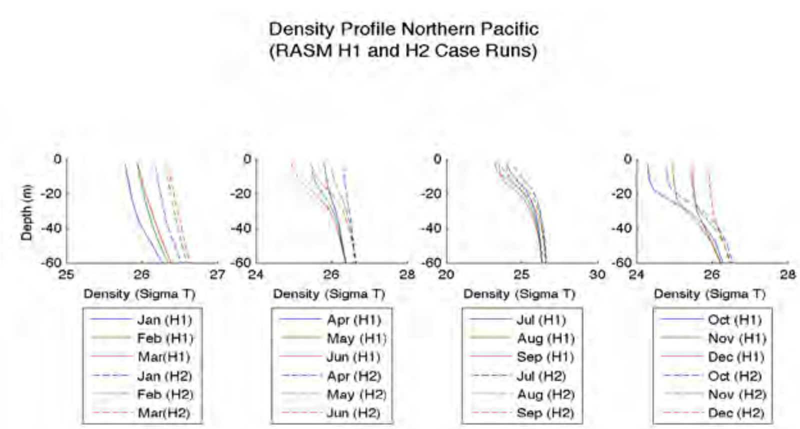

Figure 25. H1 and H2 case runs of monthly mean density profiles northern Pacific Ocean 1959–2009 and 1948–2009.

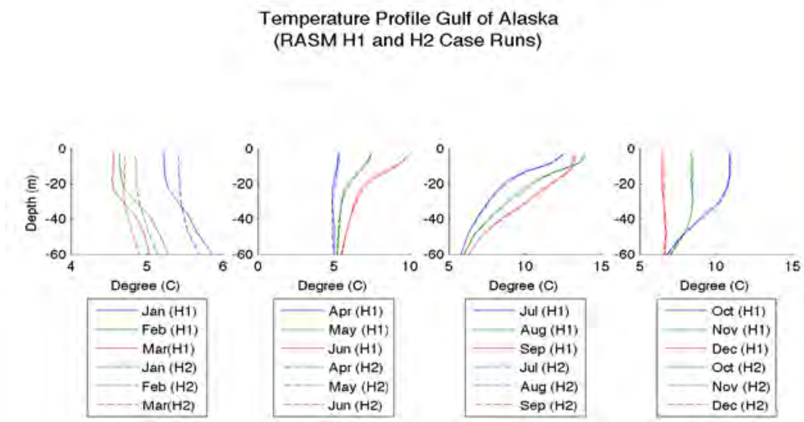

Figure 26. H1 and H2 case runs of monthly mean temperature profiles Gulf of Alaska 1959–2009 and 1948–2009.

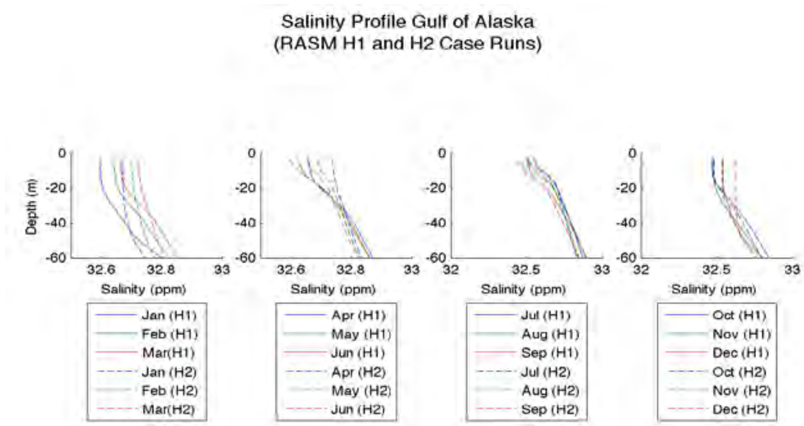

Figure 27. H1 and H2 case runs of monthly mean salinity profiles Gulf of Alaska 1959–2009 and 1948–2009.

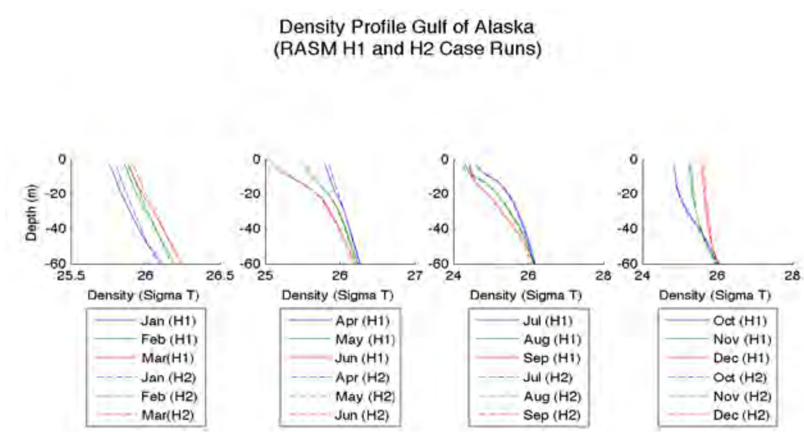

Figure 28. H1 and H2 case runs of monthly mean density profiles Gulf of Alaska 1959–2009 and 1948–2009.

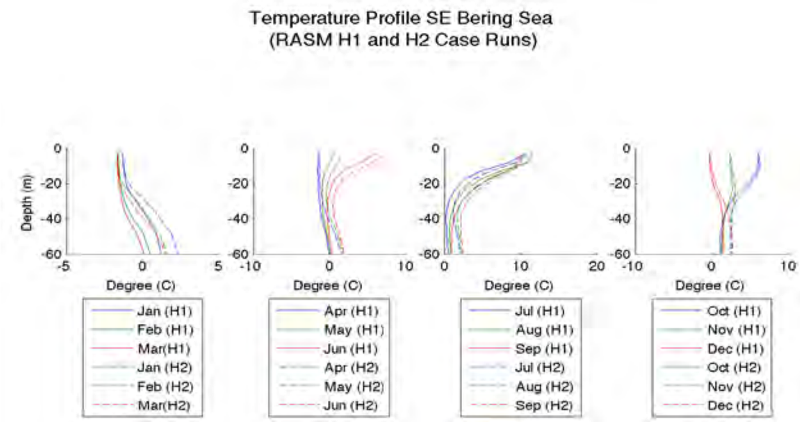

Figure 29. H1 and H2 case runs of monthly mean temperature profiles southeast Bering Sea 1959–2009 and 1948–2009.

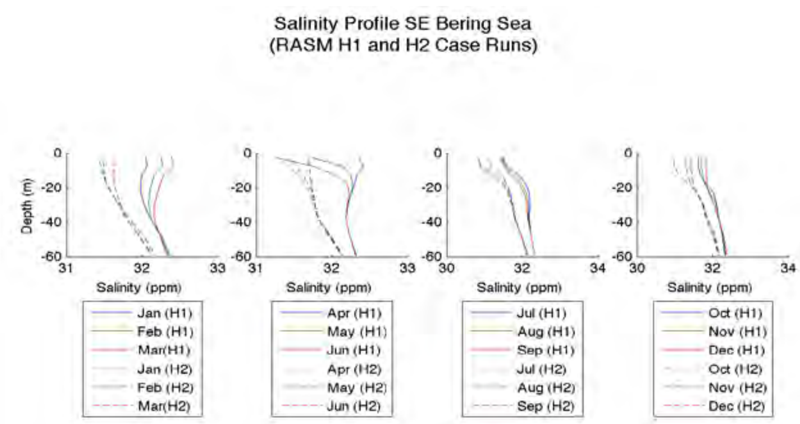

Figure 30. H1 and H2 case runs of monthly mean salinity profiles southeast Bering Sea 1959–2009 and 1948–2009.

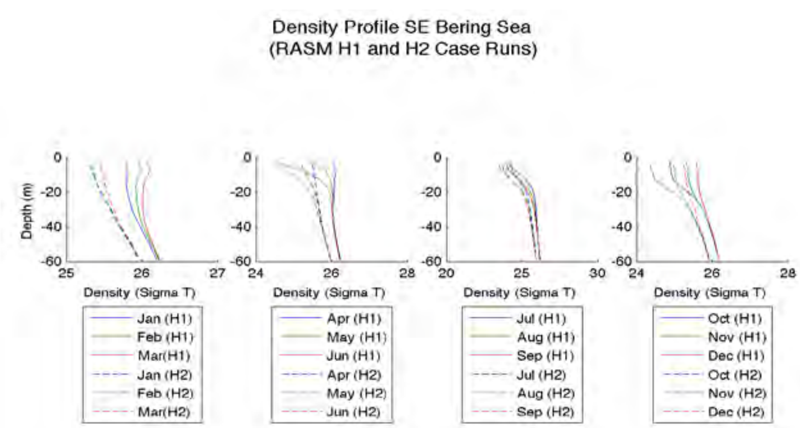

Figure 31. H1 and H2 case runs of monthly mean density profiles southeast Bering Sea 1959–2009 and 1948–2009.

B. RASM COMPARISON TO GAK1

In order to validate the RASM output from the H1 and H2 case runs we compared the results of the model runs to the GAK1 oceanographic station in the Gulf of Alaska. Observations from GAK1 provide a multi-decadal time series that is one of the longest in the North Pacific with long term means of temperature, density, and salinity (University of Alaska Fairbanks 2013). RASM SST and salinity monthly averages were produced at a small box with four points near the GAK1 station at 59° 50.7' N 149° 28.0' W. Figures 32 and 33 show monthly averaged profiles for temperature and salinity at the GAK1 station. Figures 34 and 35 show monthly averaged profiles for temperatures from the RASM H1 and H2 case runs. The H1 case run does a better job at representing the gradient in the temperature profiles for January through April than the H2 case run. The H2 case run, however, has better representation of the thermocline than the H1 case in September through January. Both cases do well in representing the overall temperatures seen at all levels within 1ºC for all months. Figures 36 and 37 show the salinity profiles for the H1 and H2 cases of RASM respectively. Overall, the H1 case run does a better job in representing the gradient in the profile for all months for salinity compared to the H2 case run. However, the H2 case run does a better job representing the halocline from July through December than does the H1 case run. Overall, both cases show salinity values around 32ppm below the halocline, which matches up well to the GAK1 profiles. Above the halocline both case runs salinity values stay near 32 where the GAK1 profile (Figure 33) reaches salinity values near 25 at the surface during the month of August. This suggests that a more realistic model representation of freshwater runoff into the Gulf of Alaska is required to better simulate salinity, which is expected to improve with the addition of river routing scheme in RASM, currently underway.

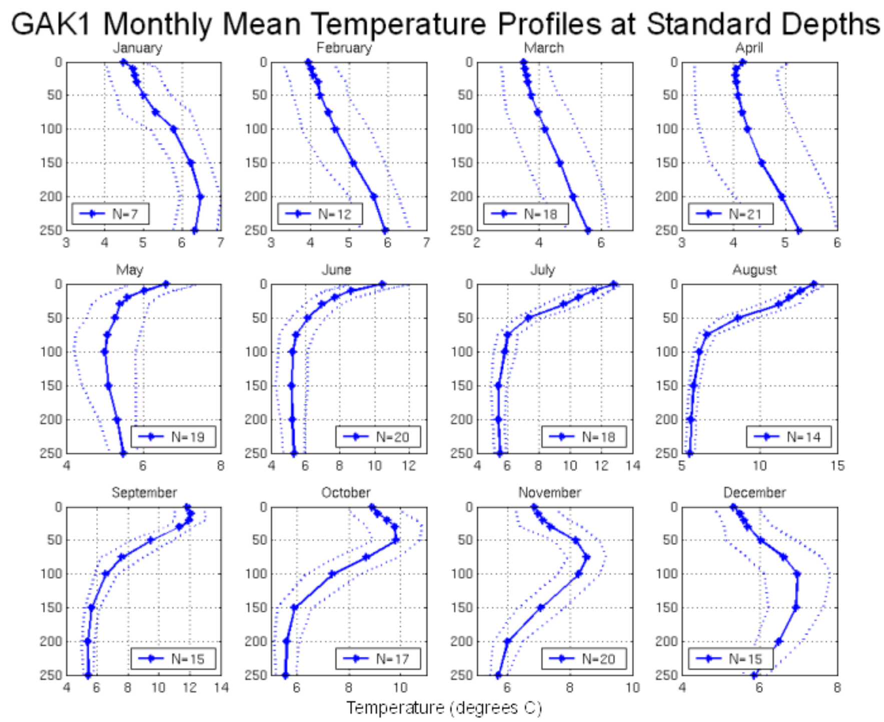

Figure 32. GAK1 monthly mean temperature profiles at standard depths (University of Alaska Fairbanks 2013).

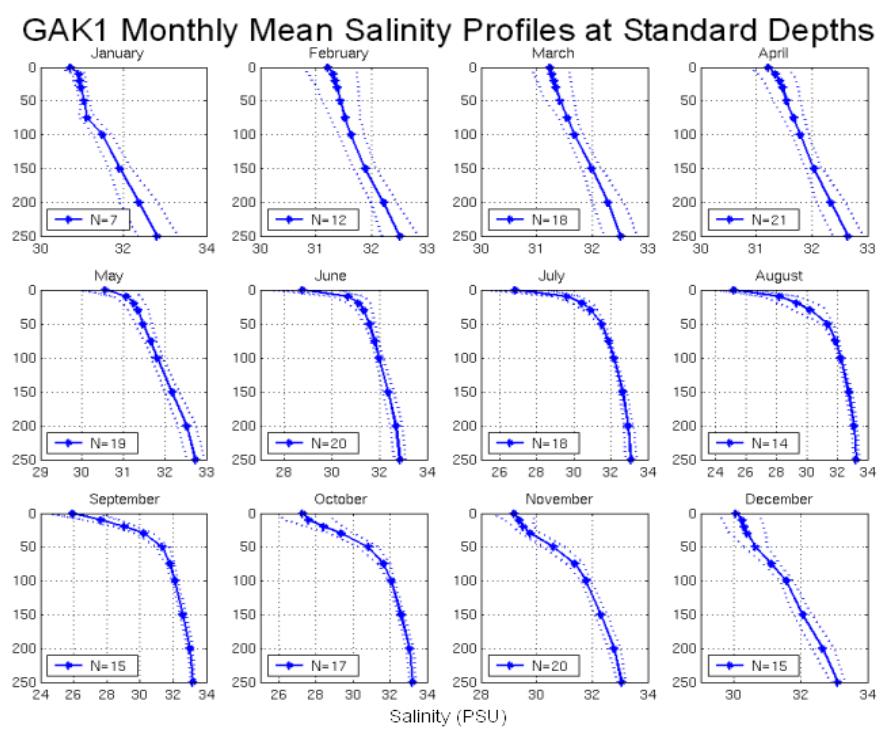

Figure 33. GAK1 monthly mean salinity profiles at standard depths (University of Alaska Fairbanks 2013).

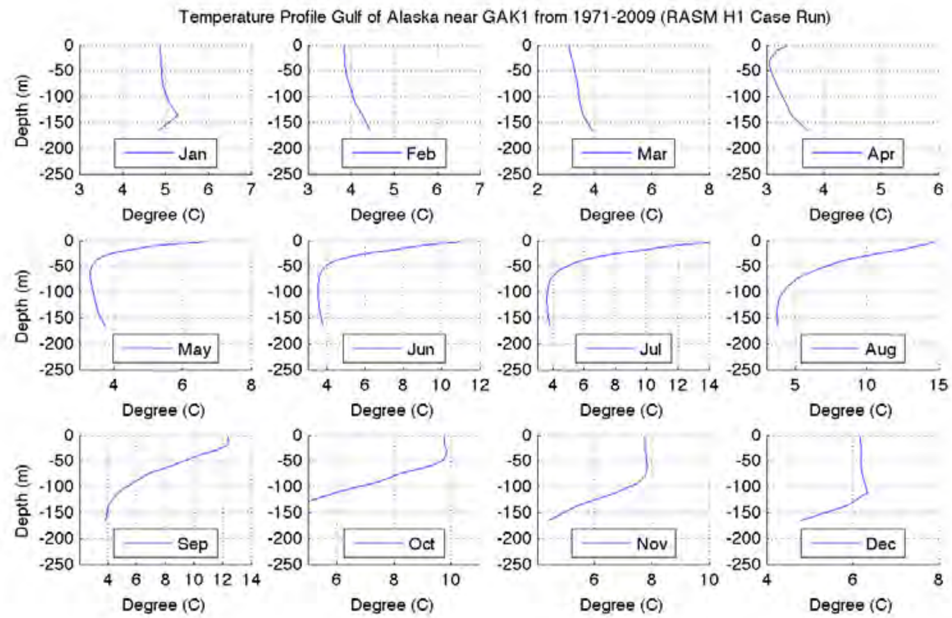

Figure 34. H1 case run monthly mean temperature profile near GAK1 from 1971–2009.

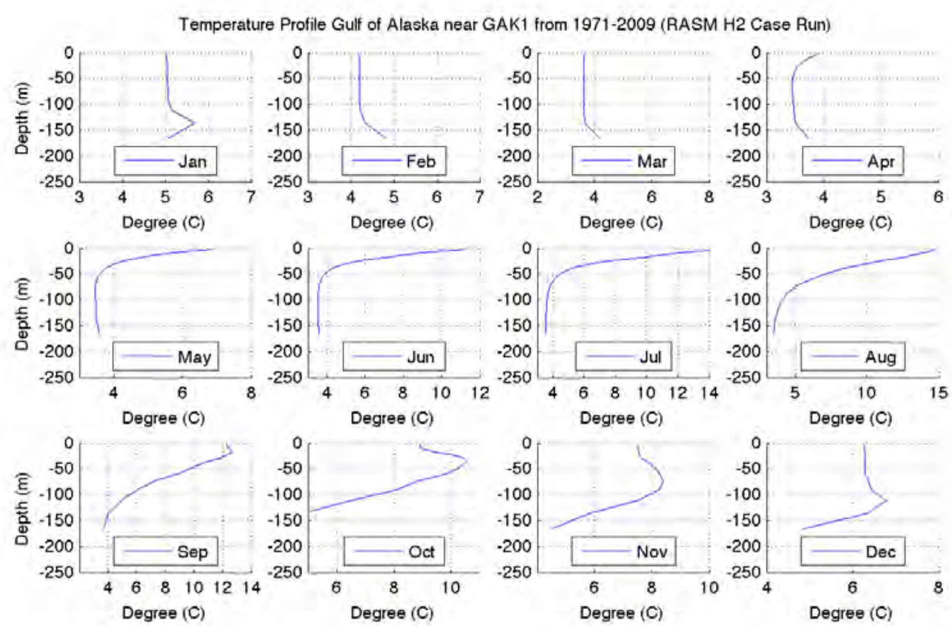

Figure 35. H2 case run monthly mean temperature profile near GAK1 from 1971–2009.

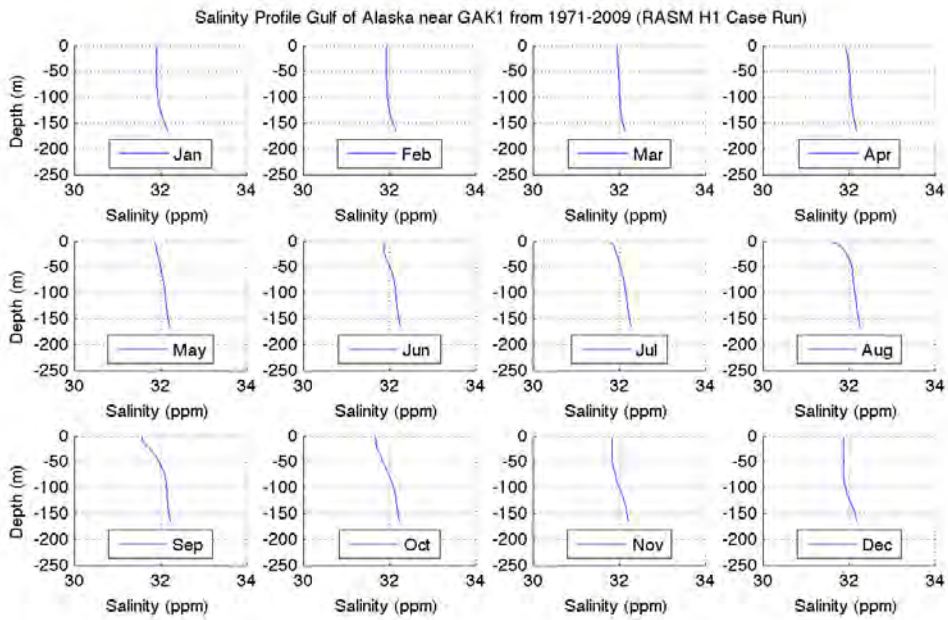

Figure 36. H1 case run monthly mean salinity profile near GAK1 from 1971–2009.

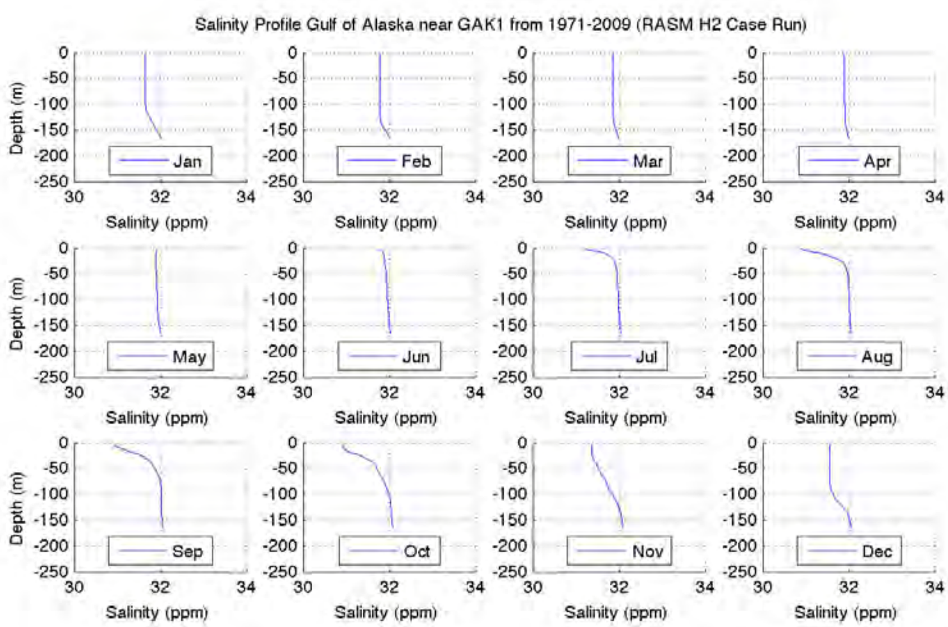

Figure 37. H2 case run monthly mean salinity profile near GAK1 from 1971–2009.

C. RASM CORRELATION TO PDO

Hare and Mantua (2000) state that PDO events show remarkable persistence lasting 20–30 years with visible fingerprints in the North Pacific/North American sector. In order to better understand the causality of climate regime shifts simulated by RASM, correlations of RASM output to PDO were conducted. In Figure 4 there is a distinct wave like pattern showing the PDO going in and out of positive and negative phases since 1900.

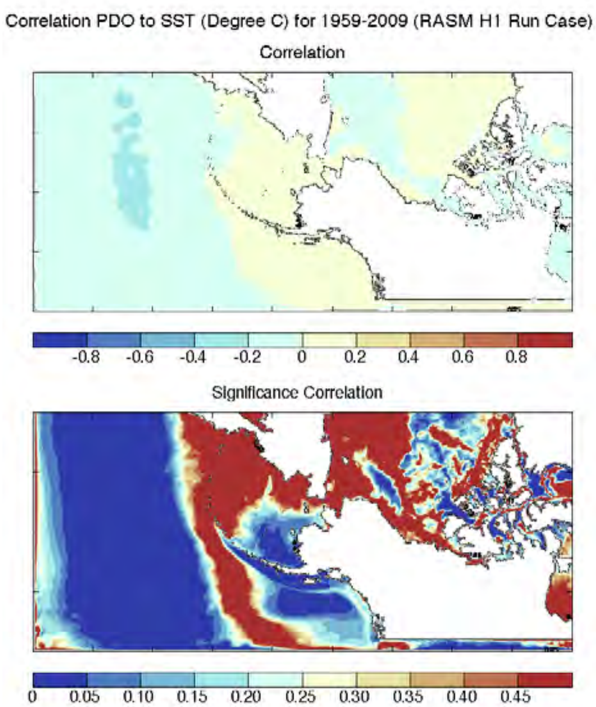

Figure 38. H1 case run SST correlation to PDO from 1959–2009 (top) with significance p-values (bottom).

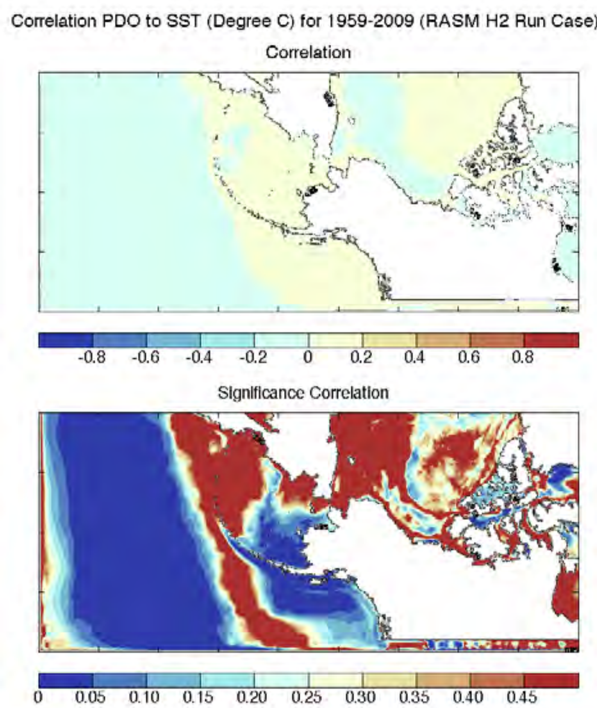

Figure 39. H1 case run SST correlation to PDO from 1959–2009 (top) with significance p-values (bottom).

The first step of the correlation process was to see if there was a correlation and if it was significant in the North Pacific region. Figures 38 and 39 show the correlation of SST monthly mean time series at each model grid cell to the PDO from 1959–2009 and the significance of the correlation. In this case we define as significant areas that have p-values of 0.05 or less. For both case runs, there is a significant, but weak correlation between the PDO and RASM in the Gulf of Alaska and the southeast Bering Sea.

The next step was to examine if correlations vary at different times of the year. Figures 40 and 41 show the winter and summer correlation of H1 and H2 case runs to the PDO from 1959–2009 for the H1 case and 1948–2009 for the H2 case. For both cases, the winter had the strongest correlation coefficients (up to 0.8) in the southeast Bering Sea and the Gulf of Alaska with significance values less than 0.05. Summer correlations were also higher in the southeast Bering Sea for both runs compared to the whole year correlations.

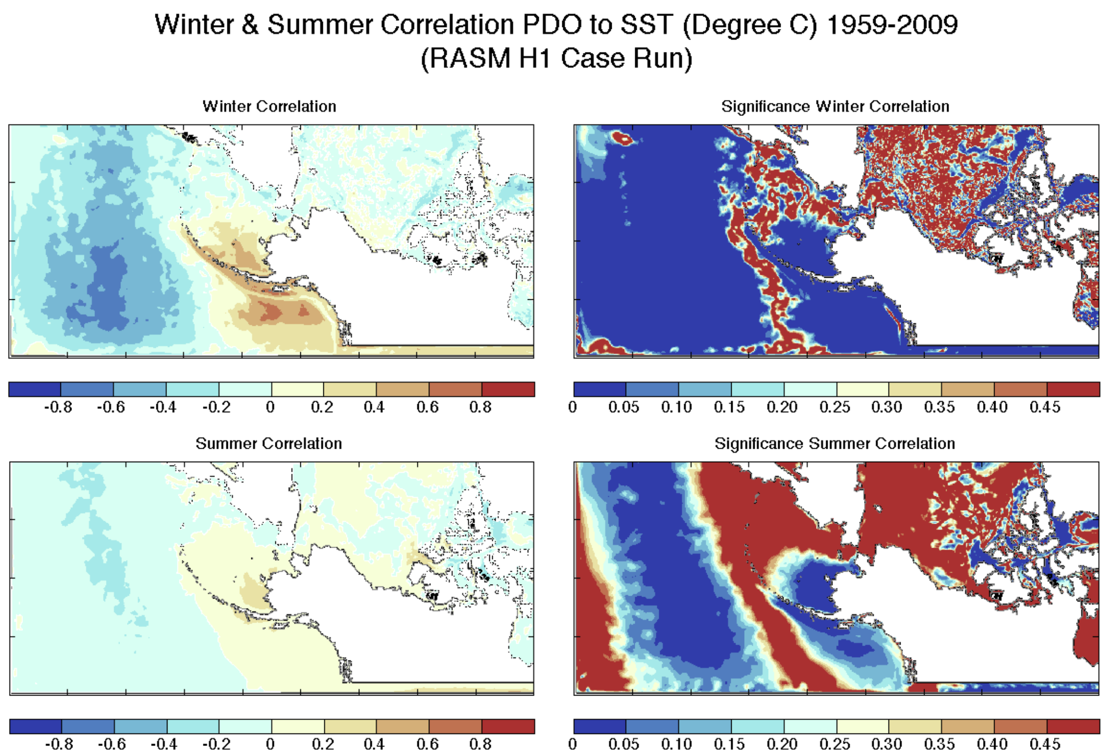

Figure 40. H1 case run winter and summer correlation of SST to PDO from 1959–2009 (top) with significance p-values (bottom).

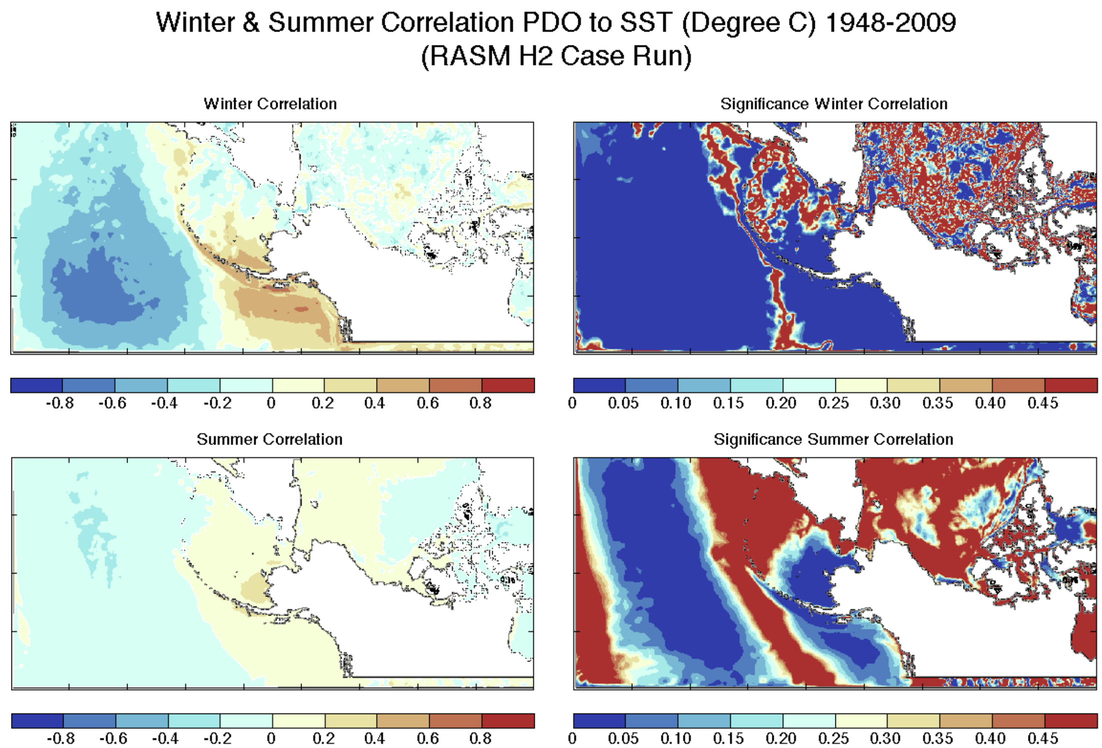

Figure 41. H1 case run winter and summer correlation of SST to PDO from 1959–2009 (top) with significance p-values (bottom).

Given such correlations between PDO and modeled SSTs, we next examined lagged correlations in the three previously analyzed regions. In figures 42–47 a +/- 50 month lag correlation was used. For all three regions and for both model runs, the strongest correlation was at 0 months and the p-values for all cases were under 0.05. This result suggests that oceanic advection is not important factor controlling SST distribution and variability. The lag at 0 months, points to the atmosphere as the main driver of SST variability in the North Pacific and Bering Sea.

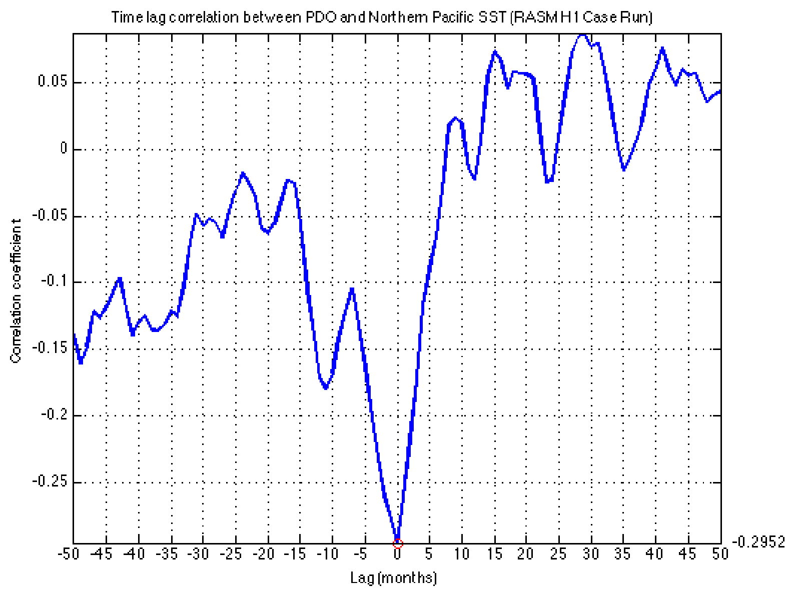

Figure 42. H1 case run time lag correlation between PDO and monthly mean north Pacific Ocean SST from 1959–2009.

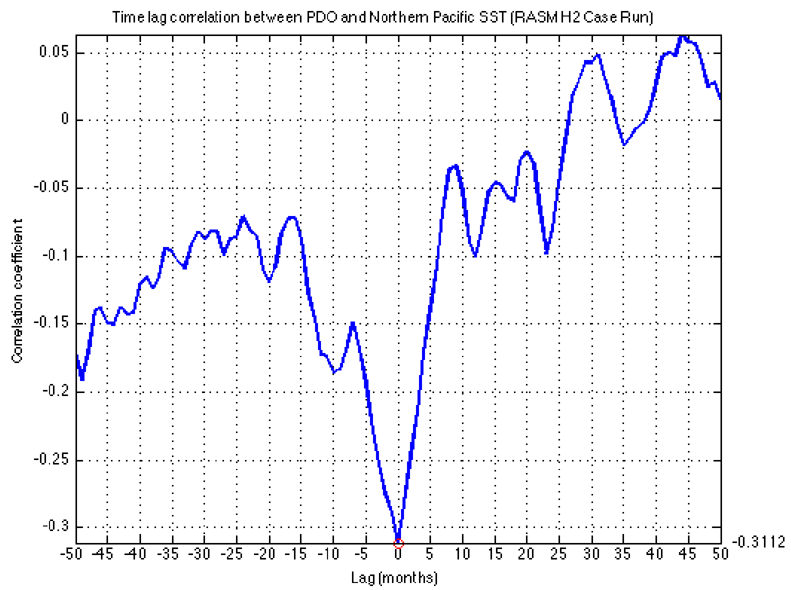

Figure 43. H2 case run time lag correlation between PDO and monthly mean north Pacific Ocean SST from 1948–2009.

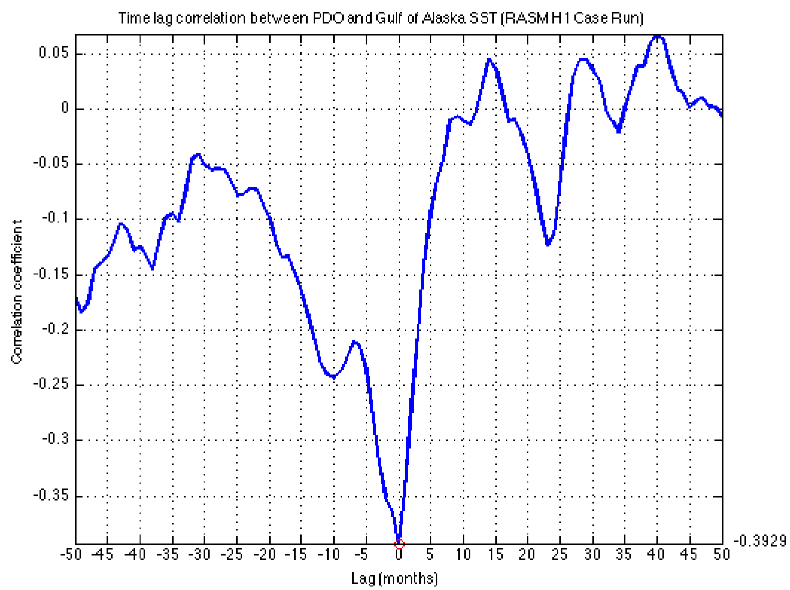

Figure 44. H1 case run time lag correlation between PDO and Gulf of Alaska monthly mean SST from 1959–2009.

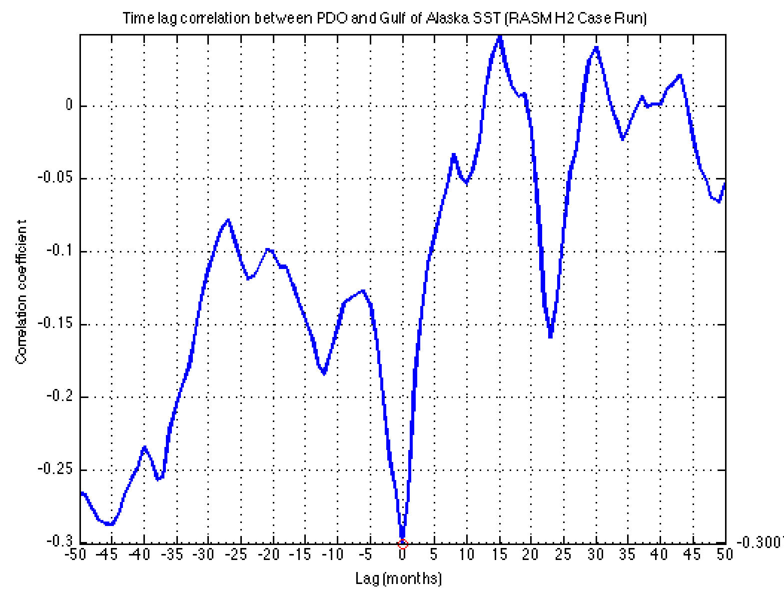

Figure 45. H2 case run time lag correlation between PDO and Gulf of Alaska monthly mean SST from 1948–2009.

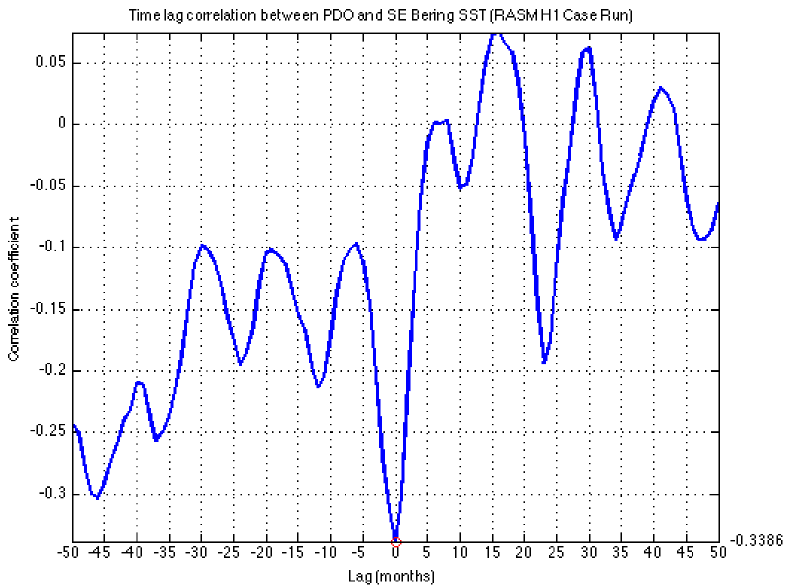

Figure 46. H1 case run time lag correlation between PDO southeast Bering Sea monthly mean SST from 1959–2009.

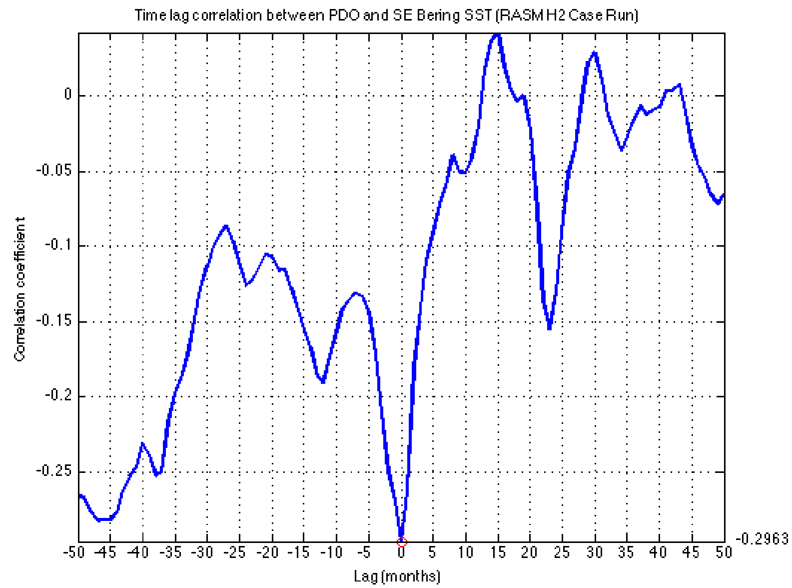

Figure 47. H2 case run time lag correlation between PDO southeast Bering Sea monthly mean SST from 1948–2009.

D. RASM COMPARISION TO CCSM4

The final analysis test and the most important was to examine if CCSM4 was able to detect climate regime shift patterns as well as RASM. The analysis was conducted in the northern Pacific Ocean, Gulf of Alaska, and southeast Bering Sea. Examining the time series and the anomalies from CCSM4 from two ensemble member runs (r3 and r4) displayed a temperature shift between 1980 and 1990 for the northern Pacific and the southeast Bering Sea (Figures 48, 49, 52, and 53). This shift appears to be an error in the data as the CCSM4 data was analyzed in three 10 year pieces (1970–1979, 1980–1989, and 1990–1999) and one five year piece (2000–2005). Since the shift falls exactly on one of the 10 year segments, that gives cause to potential data corruption. In the Gulf of Alaska the temperature shift did not seem as apparent or did not exist but overall temperature values appeared to be either too high or too low between 1980 and 1990 (Figures 50 and 51). In order to try and isolate potential issues with the CCSM4 data, another comparison was conducted between the CCSM4 and RASM data for a box covering the GAK1 oceanographic station. Figures 54 and 55 show the warmest temperature the CCSM4 output reaches is about 13ºC and the coldest it reaches is 0ºC. In Figure 41, the monthly average temperature at GAK1 was never lower than 3ºC. While RASM maximum temperatures for both case runs appear high with max temperatures around 16 ºC, it does a much better job at representing the nature of the water properties with low temperatures near 3ºC. To visualize the differences in temperatures between all the models and all the locations, a comparison of SSTs between all the model run's mean annual cycle were produced (Figures 56–63). Figures 56 and 57 show that RASM is cooler overall than CCSM4 in the northern Pacific Ocean. This could be caused by the problem (e.g., data corruption) with CCSM4 temperature output between 1980 and 1990. In the Gulf of Alaska RASM is colder than CCSM4 from January to April, warmer from April to October, and nearly the same from October through December (Figures 58 and 59). The southeast Bering Sea also shows that RASM is colder than CCSM4 from January to April and warmer from April to October, but it is colder from October to December (Figures 60 and 61). At the GAK1 station, RASM is warmer than CCSM4 for all months with both case runs (Figures 62 and 63).

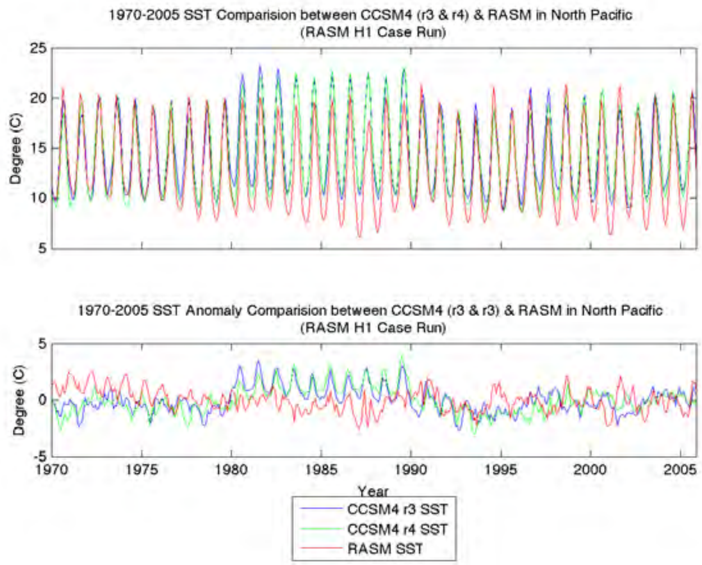

Figure 48. H1 case run monthly mean SST timeseries (top) and anomalies (bottom) comparison to CCSM4 r3 and r4 runs in the northern Pacific Ocean from 1970–2005.

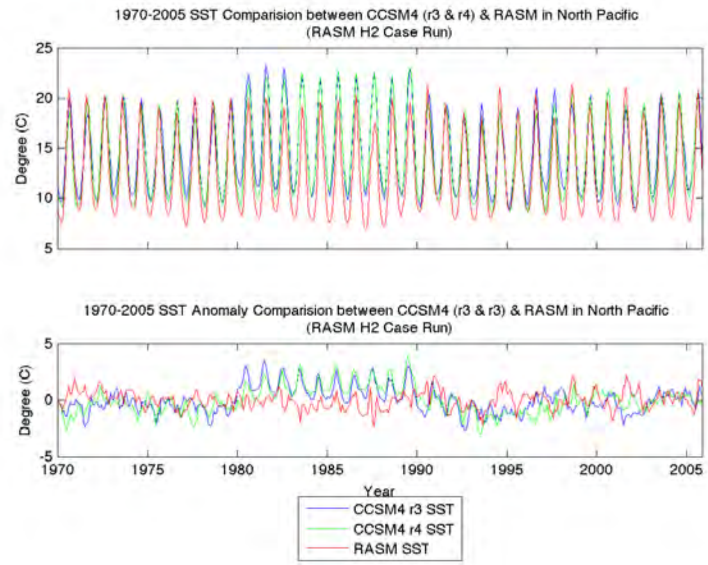

Figure 49. H2 case run monthly mean SST timeseries (top) and anomalies (bottom) comparison to CCSM4 r3 and r4 runs in the northern Pacific Ocean from 1970–2005.

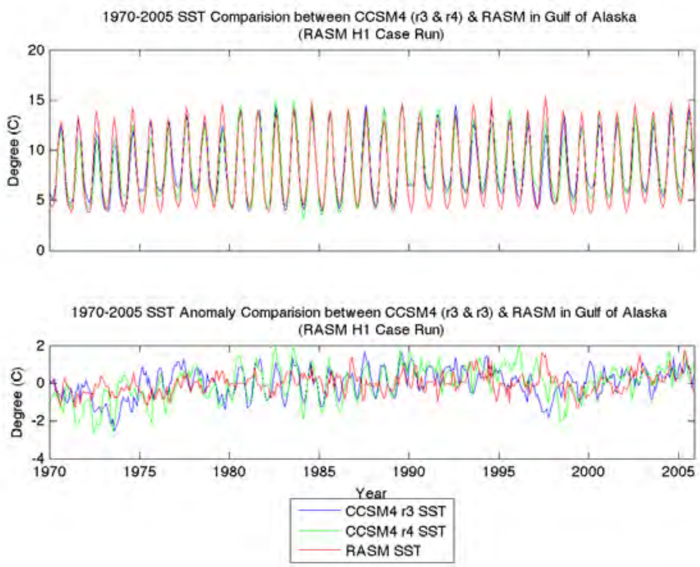

Figure 50. H1 case run monthly mean SST timeseries (top) and anomalies (bottom) comparison to CCSM4 r3 and r4 runs in the Gulf of Alaska from 1970–2005.

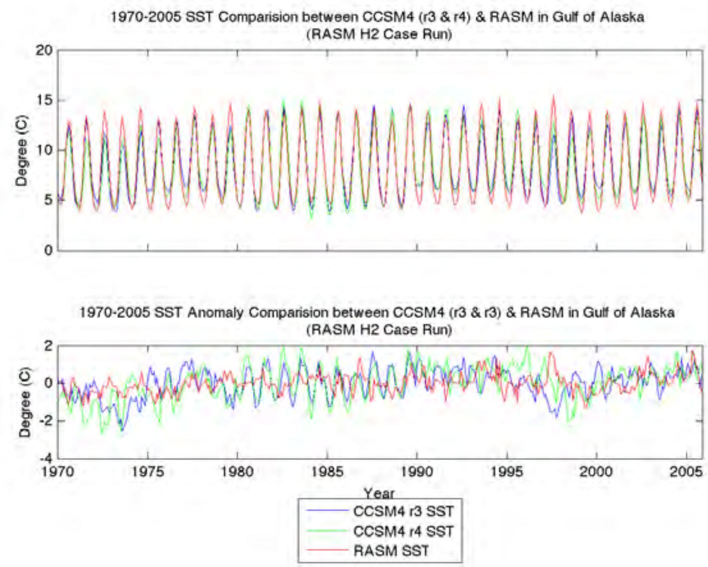

Figure 51. H2 case run monthly mean SST timeseries (top) and anomalies (bottom) comparison to CCSM4 r3 and r4 runs in the Gulf of Alaska from 1970–2005.

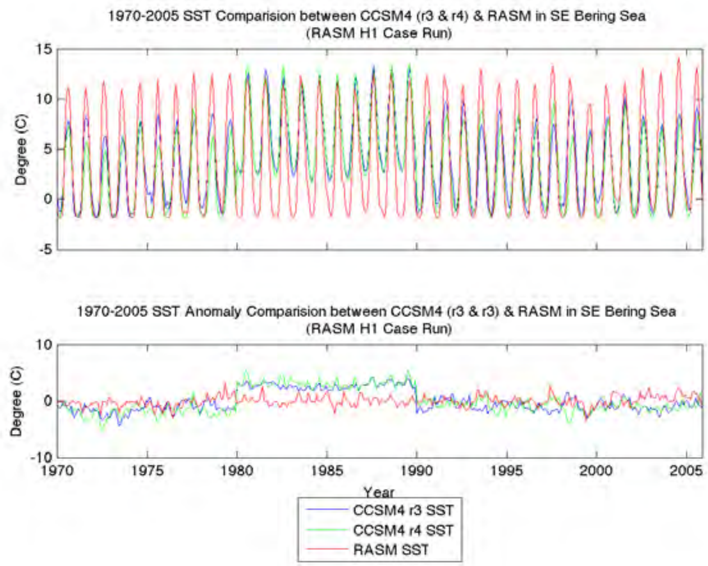

Figure 52. H1 case run monthly mean SST timeseries (top) and anomalies (bottom) comparison to CCSM4 r3 and r4 runs in the southeast Bering Sea from 1970–2005.

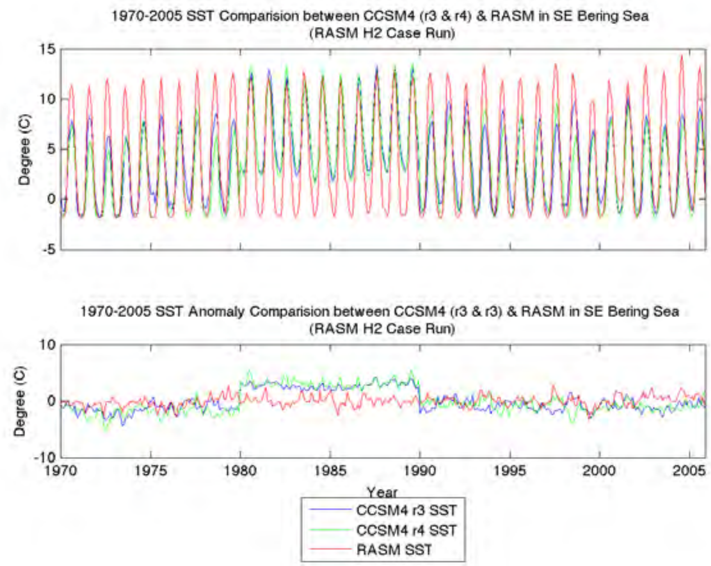

Figure 53. H2 case run monthly mean SST timeseries (top) and anomalies (bottom) comparison to CCSM4 r3 and r4 runs in the southeast Bering Sea from 1970–2005.

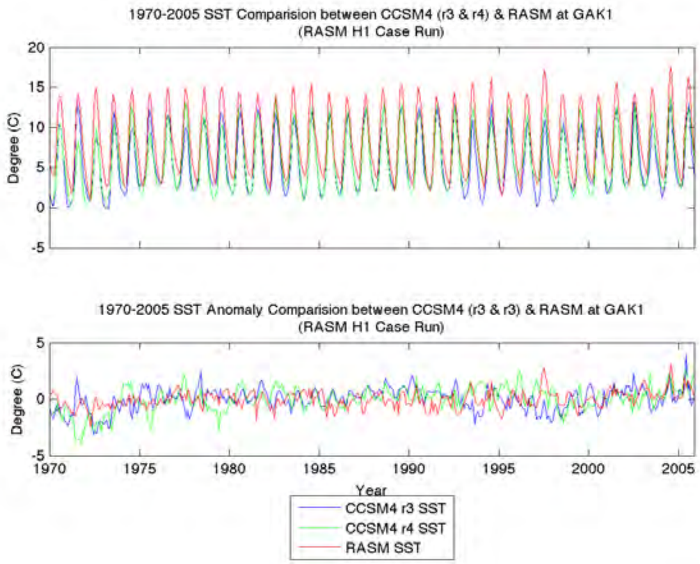

Figure 54. H1 case run monthly mean SST timeseries (top) and anomalies (bottom) comparison to CCSM4 r3 and r4 runs at the GAK1 oceanographic station from 1970–2005.

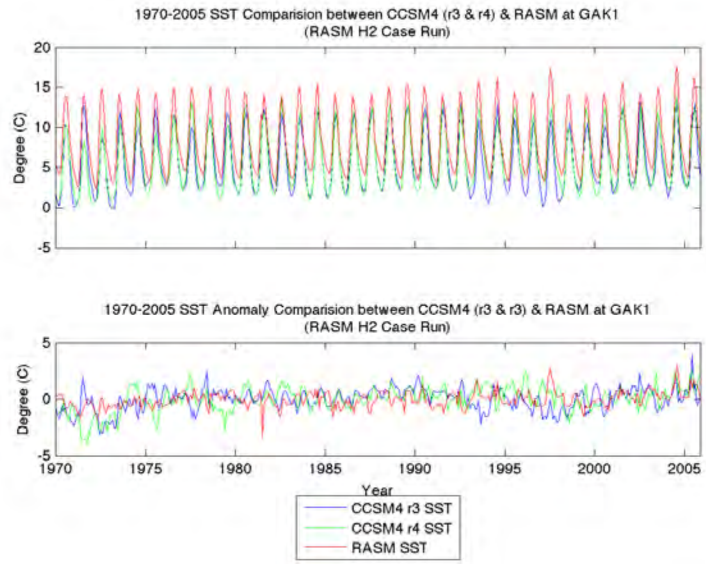

Figure 55. H2 case run monthly mean SST timeseries (top) and anomalies (bottom) comparison to CCSM4 r3 and r4 runs at the GAK1 oceanographic station from 1970–2005.

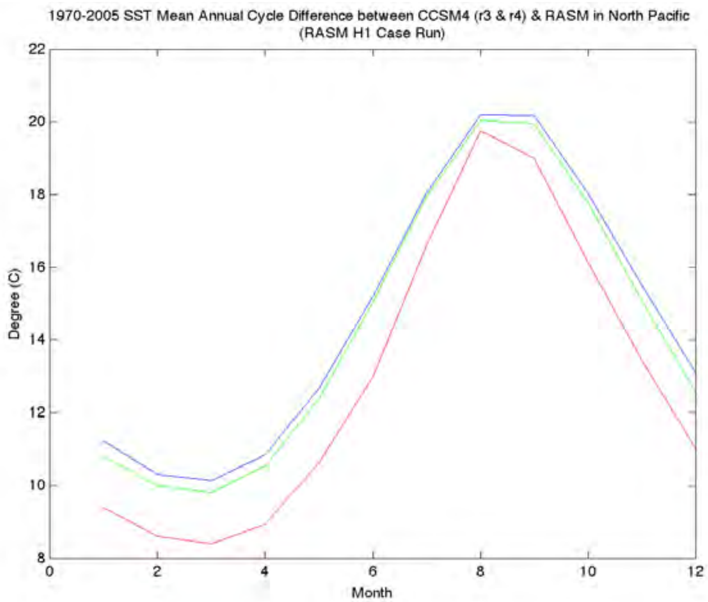

Figure 56. H1 case run mean annual cycle of monthly mean SST comparison to CCSM4 r3 and r4 runs in northern Pacific Ocean from 1970–2005.

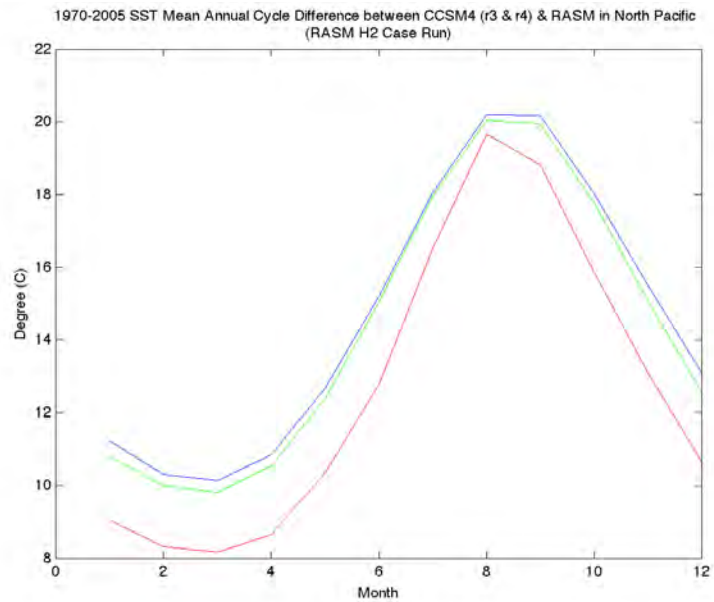

Figure 57. H2 case run mean annual cycle of monthly mean SST comparison to CCSM4 r3 and r4 runs in northern Pacific Ocean from 1970–2005.

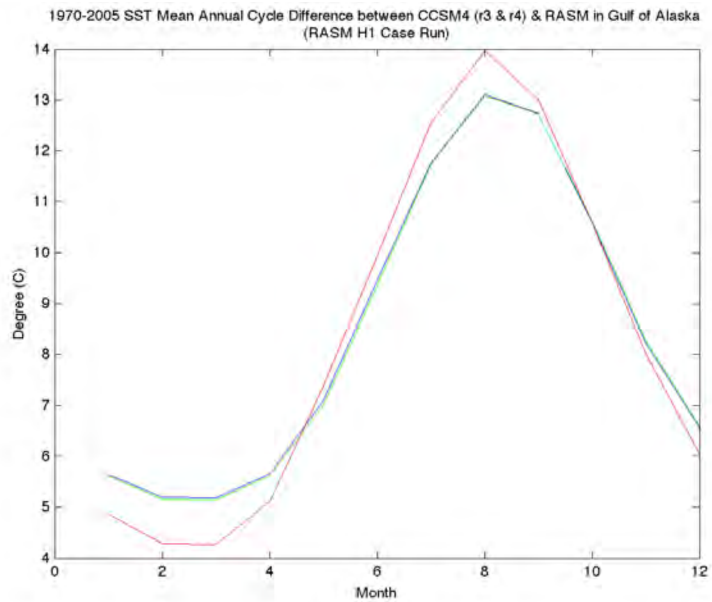

Figure 58. H1 case run mean annual cycle comparison of monthly mean SST to CCSM4 r3 and r4 runs in Gulf of Alaska from 1970–2005.

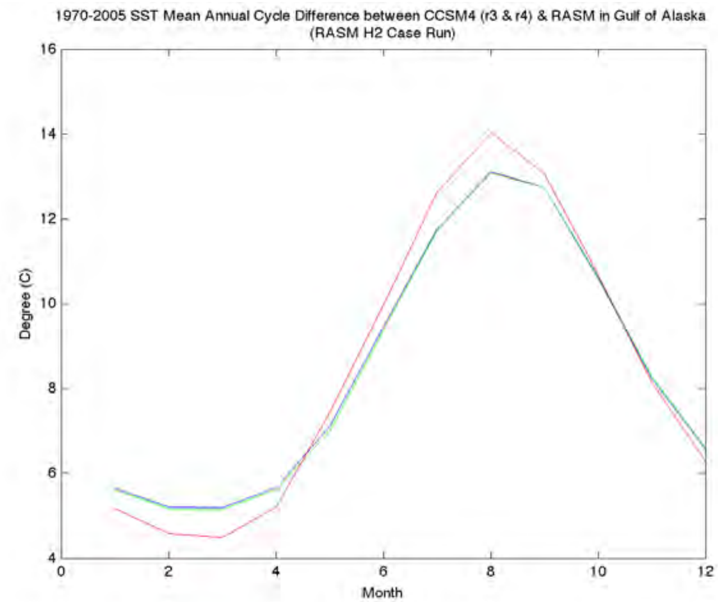

Figure 59. H2 case run mean annual cycle of monthly mean SST comparison to CCSM4 r3 and r4 runs in Gulf of Alaska from 1970–2005.

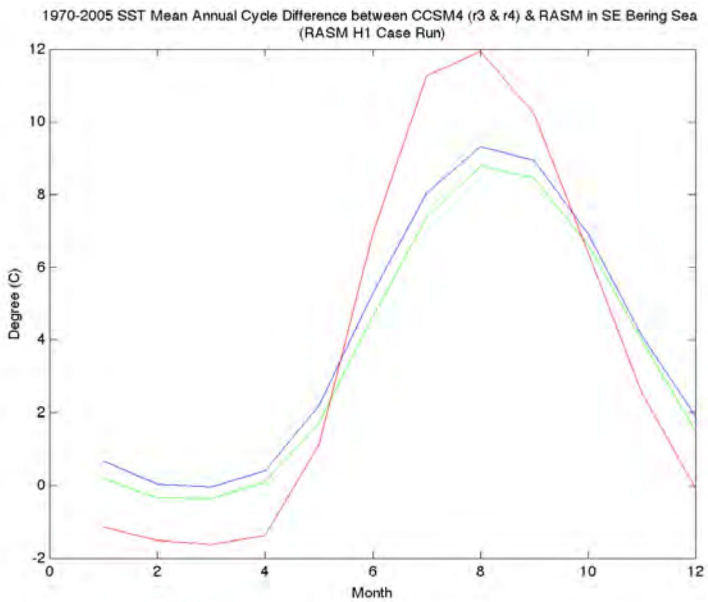

Figure 60. Figure 60. H1 case run mean annual cycle of monthly mean SST comparison to CCSM4 r3 and r4 runs in southeast Bering Sea from 1970–2005.

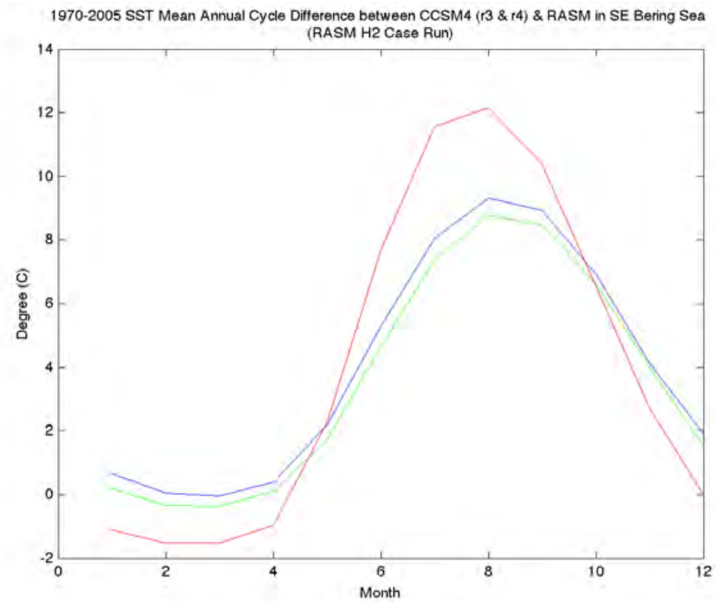

Figure 61. H2 case run mean annual cycle of monthly mean SST comparison to CCSM4 r3 and r4 runs in southeast Bering Sea from 1970–2005.

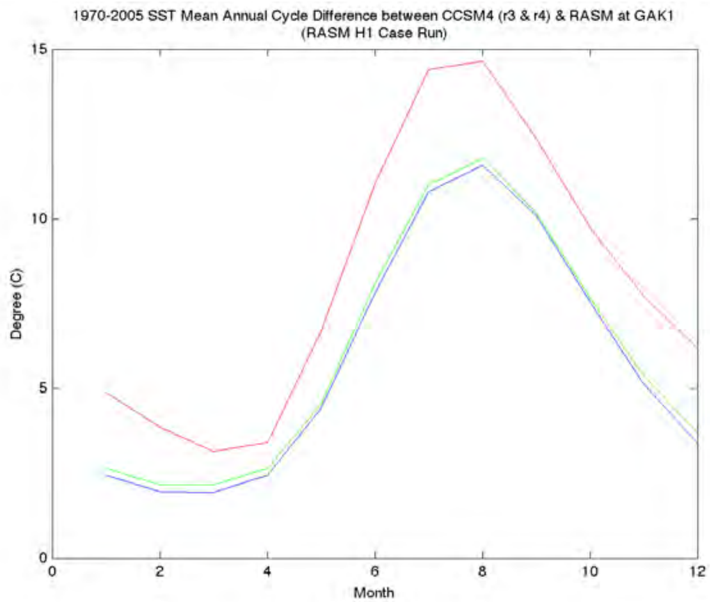

Figure 62. H1 case run mean annual cycle of monthly mean SST comparison to CCSM4 r3 and r4 runs at GAK1 oceanographic station from 1970–2005.

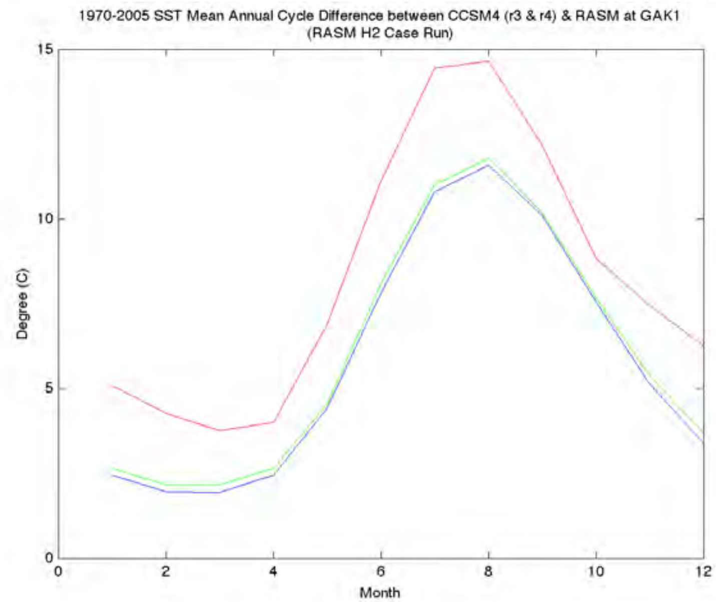

Figure 63. H2 case run mean annual cycle comparison of monthly mean SST to CCSM4 r3 and r4 runs at GAK1 oceanographic station from 1970–2005.

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V. CONCLUSION AND FUTURE RECOMENDATIONS

A. CONCLUSION

There has never been a study using 60 years of model data to study the Bering Sea, Gulf of Alaska, and northern Pacific Ocean because the data has never been available before. The model RASM used in the study allowed for detailed analysis of these regions, which are highly dynamic and influenced greatly by the changing climate and climate regime shifts. The purpose of this study was to analyze two different runs of RASM and determine the skill of the model in identifying observed climate regime shifts from SST variability as studied by Hare and Mantua (2000). Overall there are dramatic temperature shifts in RASM through analysis of monthly mean SST and heat content along with their respective monthly anomalies that provide clear evidence to a regime change occurring in the region at the observed times from Hare and Mantua (2000) in 1977, 1989, and 1997. The quality of the RASM data was compared to observations from the GAK1 oceanographic station, which demonstrated good relationship between the model and observational data not only at the surface, but through the vertical column down to 120m. The results from RASM also provided insight to correlations to the climate regime shifts and the PDO especially during the winter, however there are additional factors that have to be involved and yet to be investigated as to the causes of the regime shifts. These findings suggest that RASM compared to the CCSM4 performed better in identifying climate regime shifts, though the results were not completely conclusive due to the data corruption in the CCSM4 runs.

This analysis was by no means comprehensive but provides insight into the value added by using regional models in these highly dynamical environments. It also demonstrated the benefit of using reliable atmospheric forcing to drive to the ice-ocean model. Studying the Bering Sea, Gulf of Alaska, and northern Pacific Ocean are important as they represent the regions where Navy presence will occur first due to the seasonal variability of sea ice and absence of multi-year ice. Any operations that will occur in the high Arctic Ocean will first have to occur in these regions due to the limited capabilities within the Navy surface fleet as this time.

Regional high resolution models, such as RASM, provide the Navy means to better understand the Arctic, especially the Bering Sea and northern Pacific Ocean, as the Navy and DoD make strategic plans for future operations in the region. Maslowski et al. (2012) stated that the development and use of high-resolution Arctic climate and systems models are important stepping stones for dedicated studies of regional processes and feedbacks in the coming decade.

B. FUTURE RECOMMENDATIONS

This study concentrated on analysis of just the PDO climate index and the CCSM4 global climate model. Future studies could examine how well RASM does in identifying climate regime shifts in the Bering Sea through correlations to other climate indices such as the AO or PNA. Also, examine the performance of other EC/GCMs in simulating climate regime shifts to confirm if CCSM4 is representative of the skill of many global models in the North Pacific or an outlier. The runs of RASM analyzed were not fully coupled model runs, as the atmospheric component was replaced with the prescribed realistic atmospheric reanalyzed data to force the ice-ocean model. Next step would be to evaluate a fully coupled RASM to identify any differences or improvements in simulated statistics of SST and heat content compared to this analysis.

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